

Summary & analysis of the critical power amplifier design tool - Linearity loadpull characterization

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- *Non-50 Ohm Linearity measurement history*
- *The challenge of 2 tone test on unmatched device*
- *A novel 2 tone measurement solution → **MT2000!***
- *Beyond active loadpull*
- *System Offering*

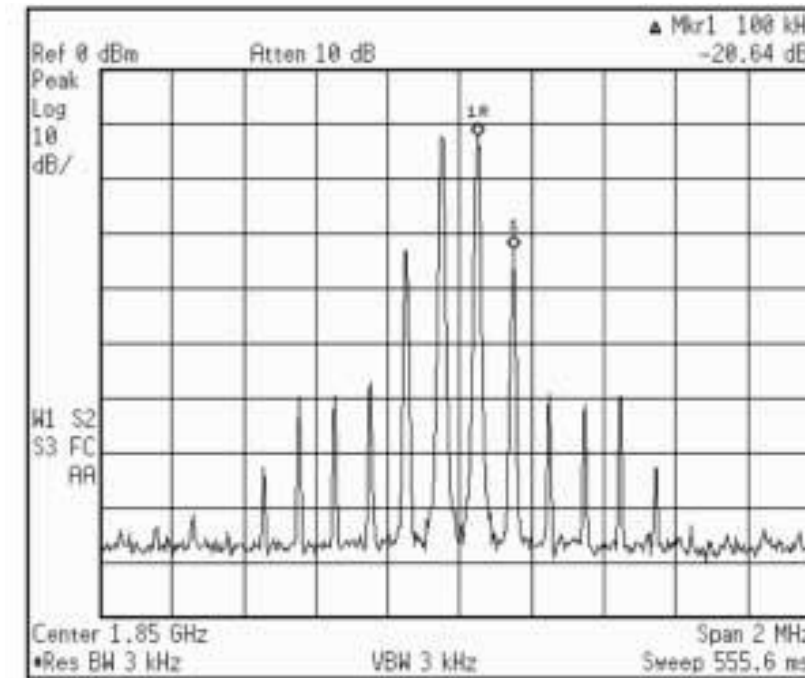
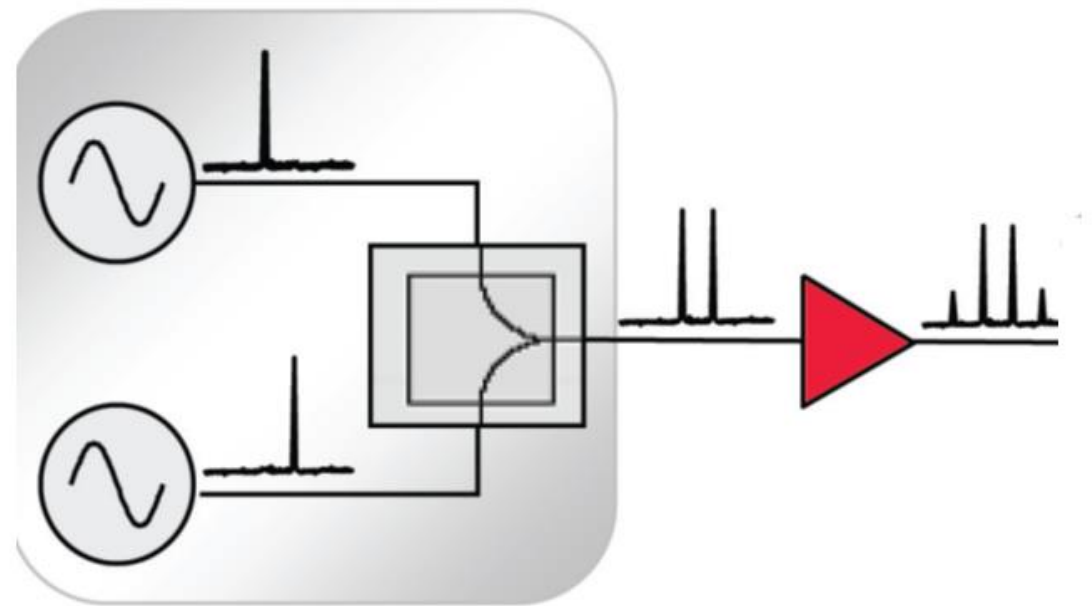
Non-50 Ohm Linearity measurement history



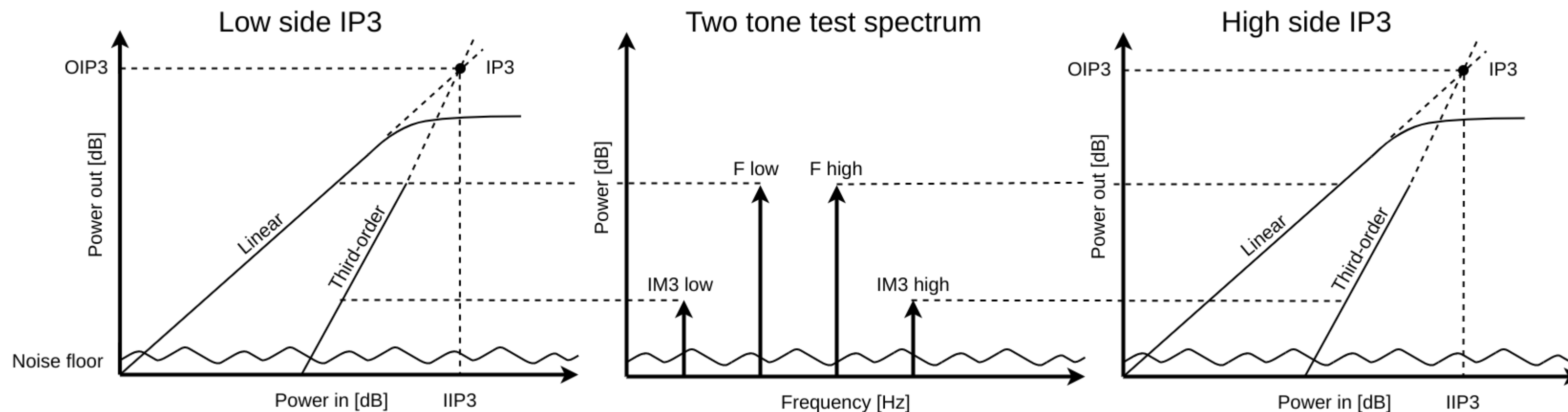
Introduction

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Intermodulation distortion (IMD) is a measurement of the nonlinearity of amplifiers and sometimes even passive components.



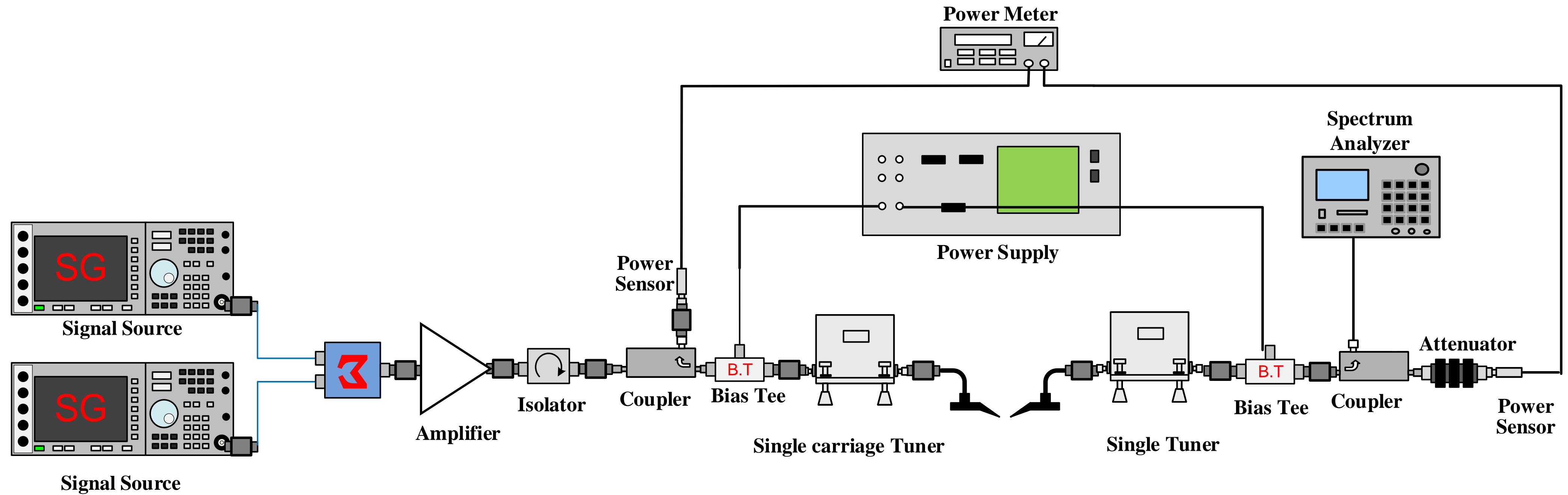
The third-order intercept point (IP3) or the third-order intercept (TOI), often used interchangeably, are figures of merit for intermodulation distortion.

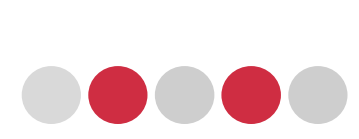


$$IP3 \text{ (dBm)} = P(f_1) + (P(f_2) - P(2f_1 - f_2)) / 2$$

Traditional 2 tone/ACPR measurement

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Calibration routine

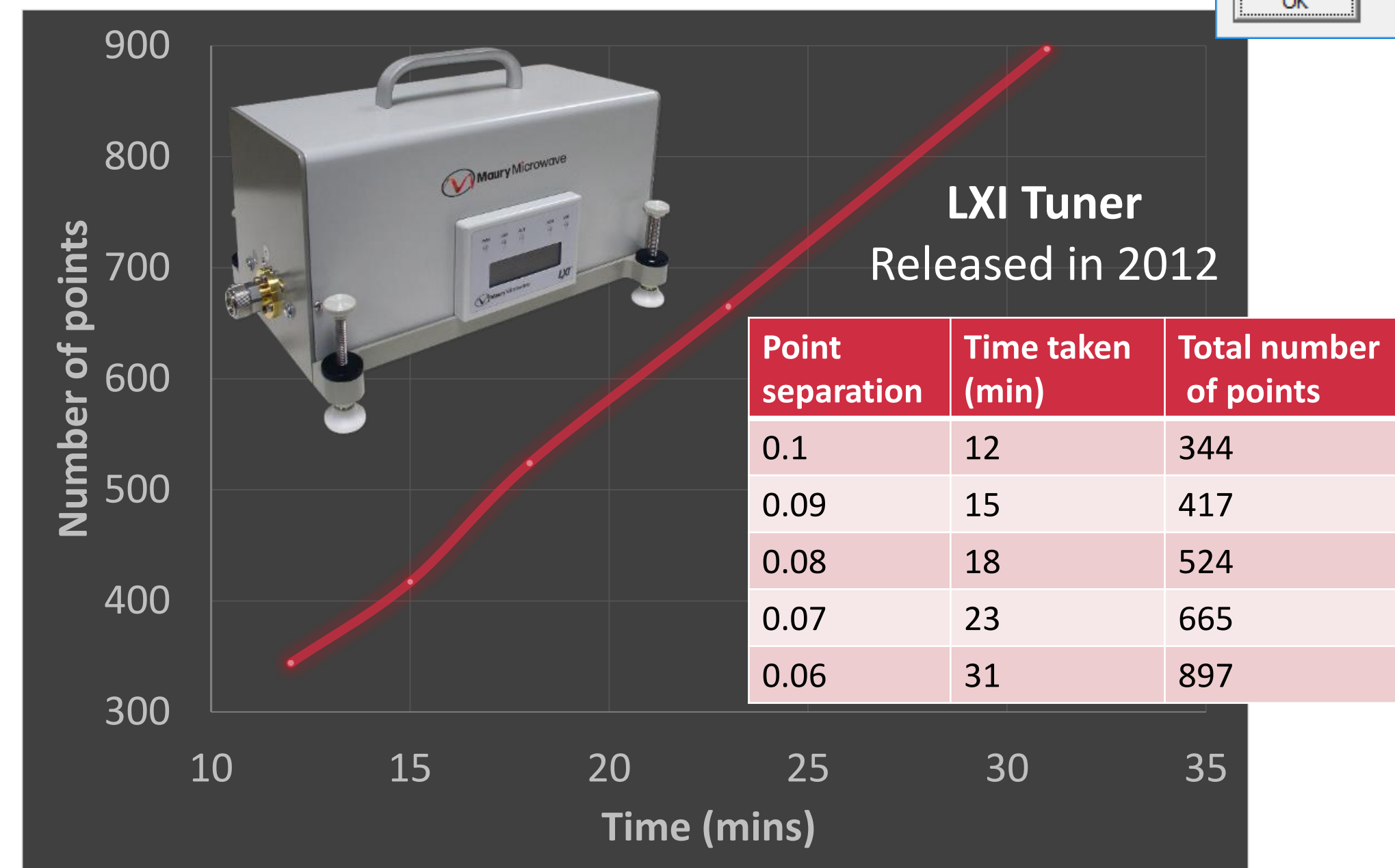
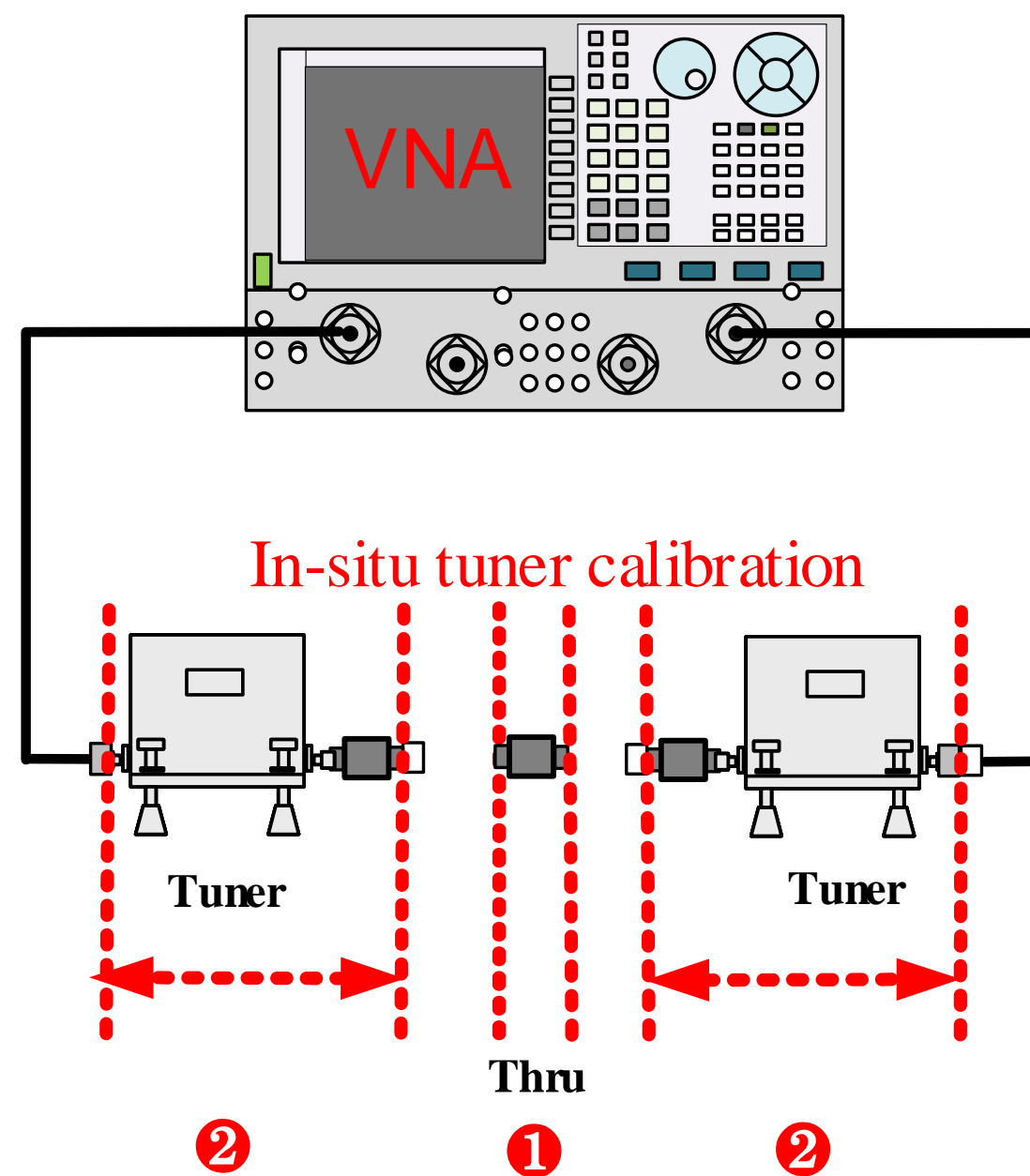
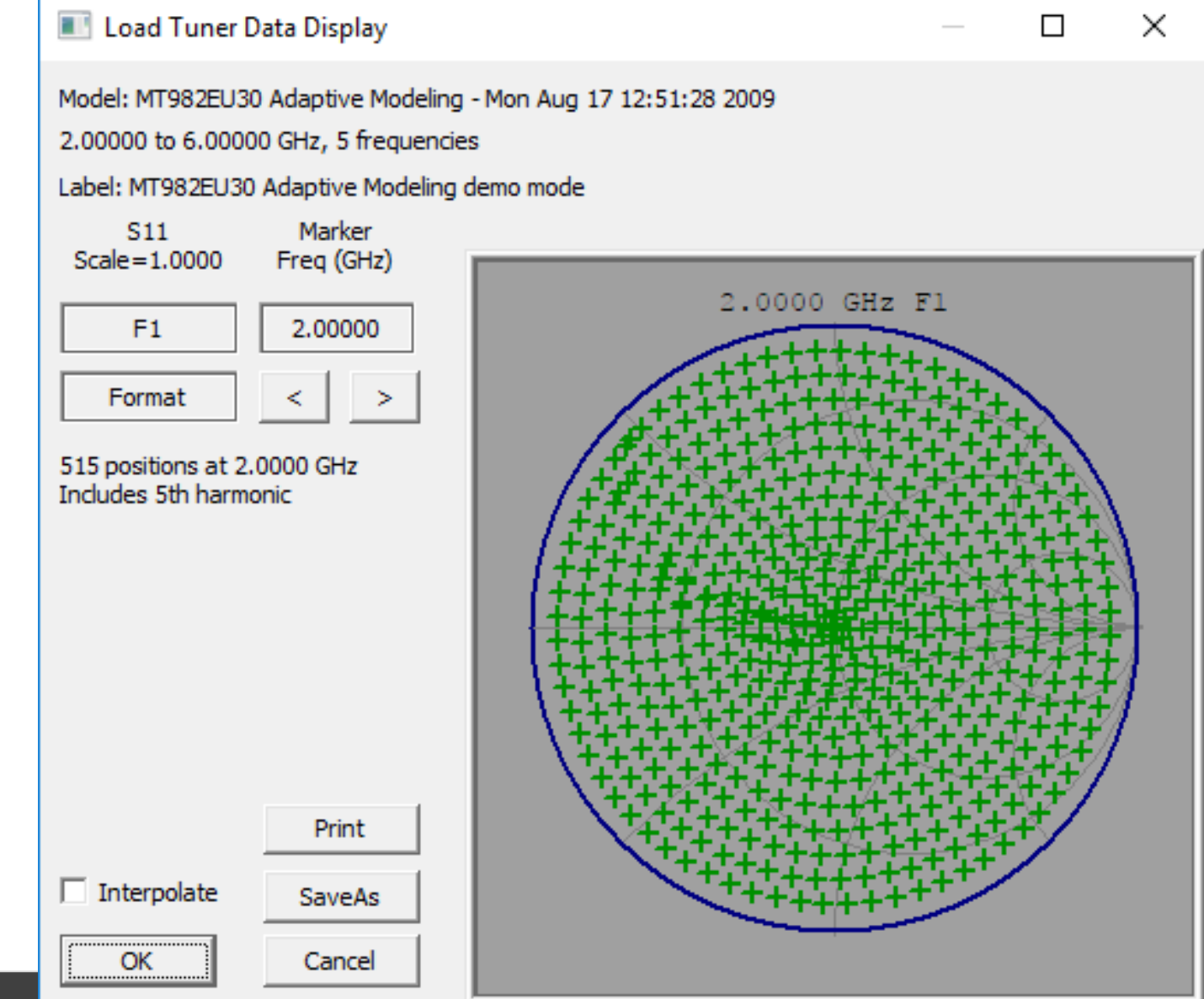
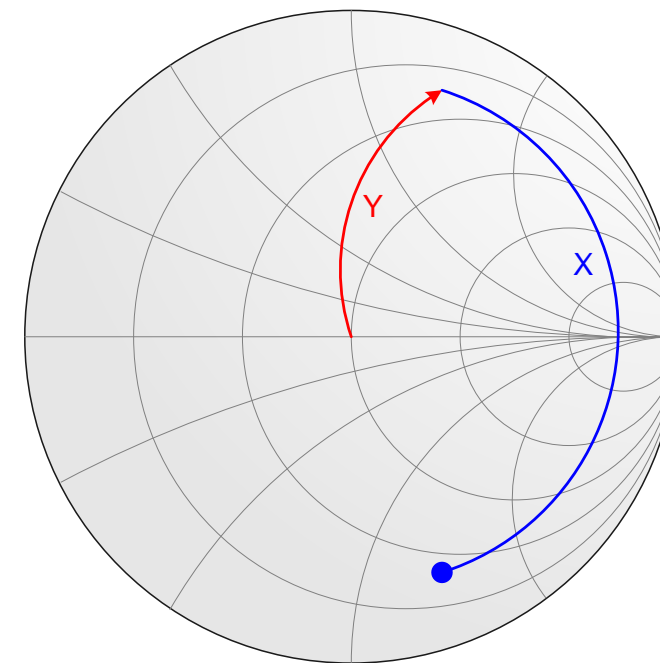
Traditional loadpull for 2 tone measurement

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1. *Non 50 Ohm characterization -> tuner calibration*
2. *Hardware connection -> manual setting of spectrum analyzer and synchronization, 10MHz synchronization*
3. *Power calibration -> sweep each tone space and each power level, generate a data base table*
4. *Measurement -> recall the table, sweep step by step*

●●●● Tuner calibration

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XT Tuner
Released in 2018
XT98xxxx Tuner
Internal microprocessor
Improved accuracy and
mechanical speed

Tuner calibration, critical and inevitable step, but TEDIOUS!

Power calibration with tone balancing

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Options Setup

System | Noise | Power | **Intermod** | ACP | Pulse | User

Tone Spacing (MHz): 5

Tone Equality (dB): 0.2

Span Ratio (max=1.0): 0.5

Min SA Atten (dB): 10

Carrier Averaging: 1

Intermod Averaging: 2

SA IP3 (dBm): 15

Optimum SA Power (dBm)
Auto Meas
Fixed -30

Imod Measurement Method
Peak Search Zero Span

OK Cancel Help

Power Calibration (Intermod)

Frequencies (GHz)
Available: 2.000 GHz to 6.000 GHz, 5 Freqs
2.0000 Add Point Add Range
Delete Point Delete All
Set to Available Frequencies

Power range (dBm)
Programmed Power Specify power at Cal Plane
-15.0000 -14.0000 -13.0000 -12.0000 -11.0000 -10.0000 -9.0000 -8.0000 -7.0000 -6.0000 -5.0000 -4.0000
Add Point Add Range
Delete Point Delete All
Gamma_s Cal Power (dBm) 10
Offset of RF Source 2 compared to RF source 1 (dB): 0

Thru s-parameters
S-parameter file name:
thrud.s2p Browse

Instrument Initialization
Power Measuring Instrument: Power Meter
Tuners: ☐ Already Initialized ☒ Initialize Now
Power Meters: ☐ Do Nothing ☒ Zero ☐ Init Sensors ☐ Calibrate
☒ Prompt to connect thru after initialization

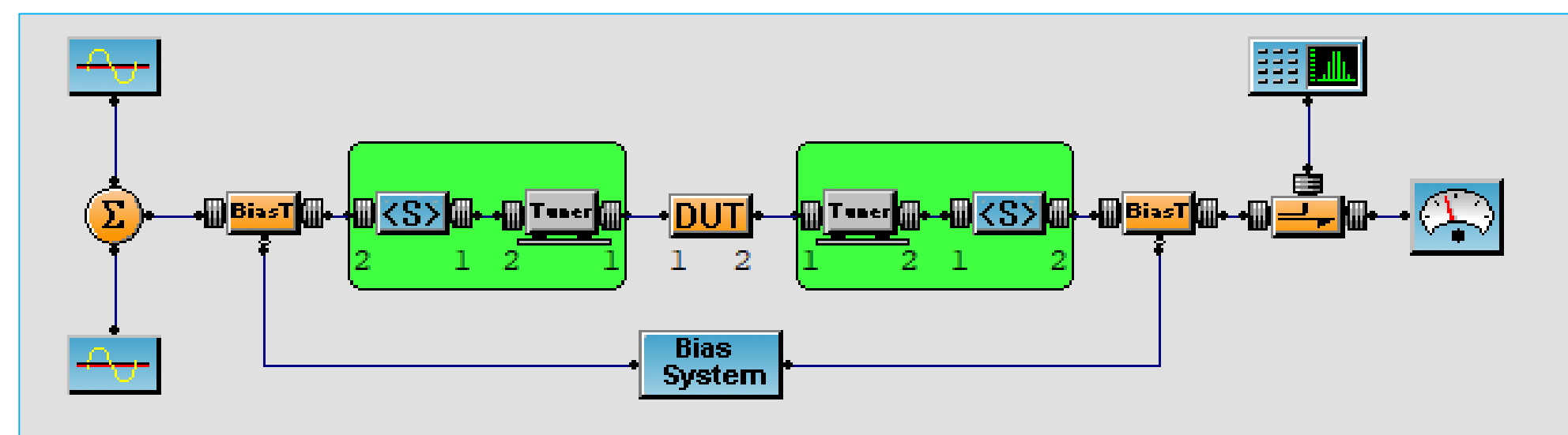
OK Cancel

Snw - [Power Calibration (Intermod)]

File Edit Window Help

Label: two_tone_power_cal_1MHz

| Freq GHz | Isource mag | Isource phase | P_programmed dBm | P_avail dBm | SA_coupling dB |
|----------|-------------|---------------|------------------|-------------|----------------|
| 2.0000 | 0.056 | 150.66 | -30.000 | -34.416 | -10.091 |
| | | | -29.000 | -33.377 | |
| | | | -28.000 | -32.399 | |
| | | | -27.000 | -31.406 | |
| | | | -26.000 | -30.406 | |
| | | | -25.000 | -29.404 | |
| | | | -24.000 | -28.397 | |
| | | | -23.000 | -27.407 | |
| | | | -22.000 | -26.404 | |
| | | | -21.000 | -25.408 | |
| | | | -20.000 | -24.409 | |
| | | | -19.000 | -23.409 | |
| | | | -18.000 | -22.413 | |
| | | | -17.000 | -21.415 | |
| | | | -16.000 | -20.417 | |
| | | | -15.000 | -19.412 | |
| | | | -14.000 | -18.414 | |
| | | | -13.000 | -17.410 | |
| | | | -12.000 | -16.406 | |
| | | | -11.000 | -15.405 | |
| | | | -10.000 | -14.385 | |
| | | | -9.000 | -13.386 | |
| | | | -8.000 | -12.385 | |
| | | | -7.000 | -11.381 | |
| | | | -6.000 | -10.370 | |
| | | | -5.000 | -9.364 | |
| | | | -4.000 | -8.344 | |
| | | | -3.000 | -7.329 | |
| | | | -2.000 | -6.308 | |
| | | | -1.000 | -5.295 | |
| | | | 0.000 | -4.258 | |
| | | | 1.000 | -3.222 | |
| | | | 2.000 | -2.176 | |
| | | | 3.000 | -1.133 | |
| | | | 4.000 | -0.082 | |
| 5.0000 | 0.085 | -71.66 | -30.000 | -34.408 | -10.516 |
| | | | -29.000 | -33.386 | |
| | | | -28.000 | -32.383 | |
| | | | -27.000 | -31.397 | |
| | | | -26.000 | -30.384 | |



●●●● pros and cons

Traditional loadpull based on power meter was the only choice in last century

- *Tedious tuner calibration*

Rely on de-embedding all the way

- *Elaborate setting/verification of system*

For accurate and relatively fast measurement

- *Exact power cal.*

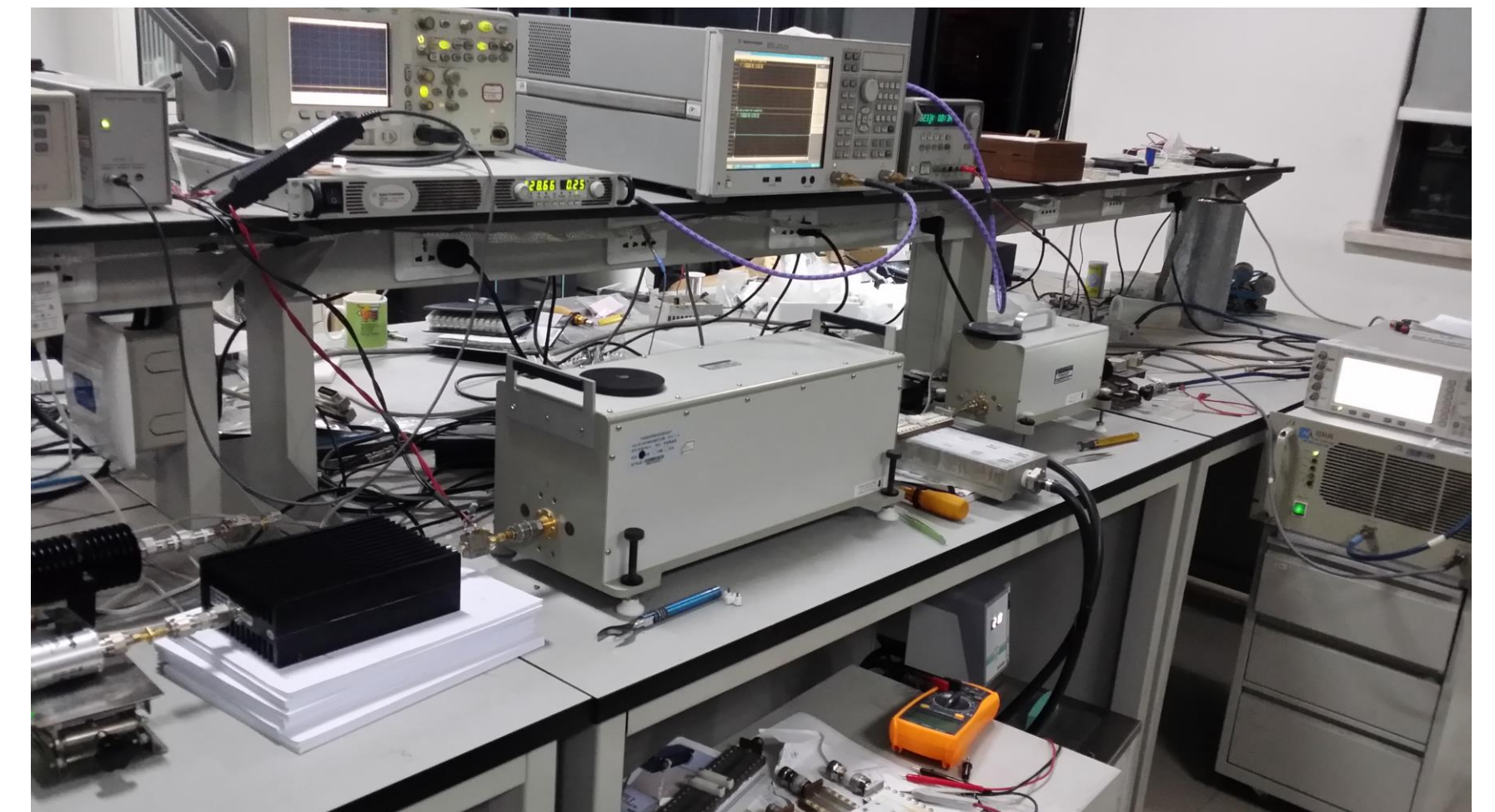
Table should be created before measurement, if driving amplifier changed, the table should be updated again.

- *Not cheap and complex to setup*

Spectrum analyzer should be connected

- *Operator should be experienced enough*

- *Cheap at the first glance, but unfortunately **NOT** in long term view*



●●●● VNA's advanced features for simple 2 tones test

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IMD measurement challenges

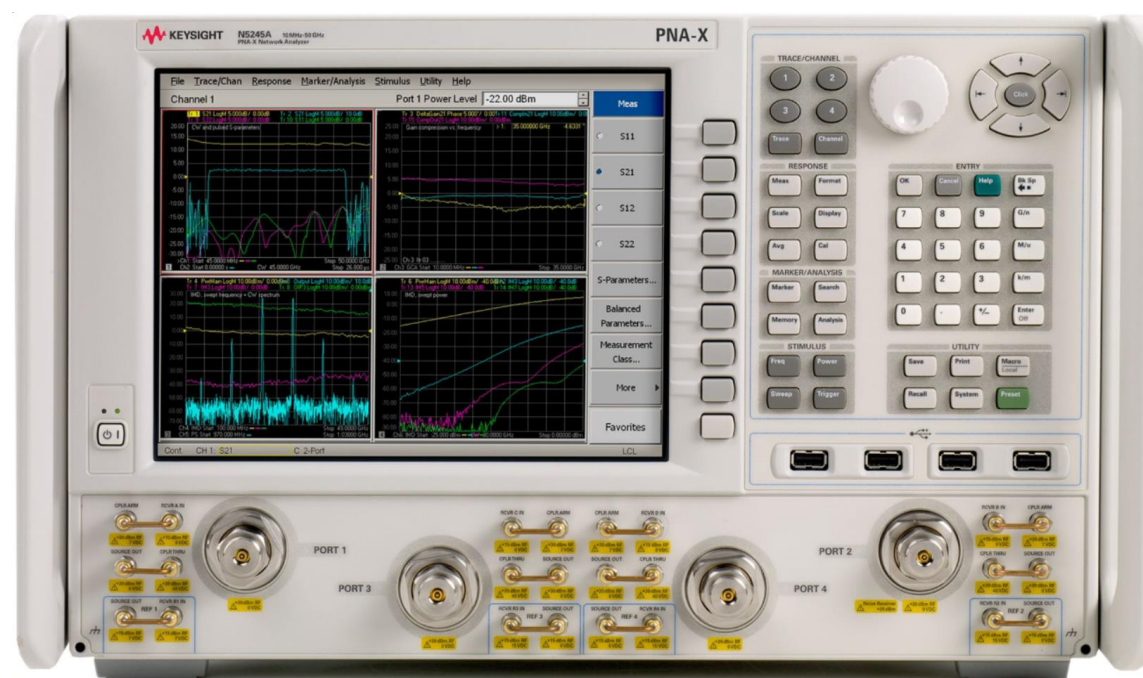
- Two signal generators, a spectrum analyzer, and an external combiner are most commonly used, requiring manual setup of all instruments and accessories
- Test times are slow when swept-frequency or swept-power IMD is measured
- Instruments and test setups often cause significant measurement errors due to source-generated harmonics, cross-modulation, and phase noise, plus receiver compression and noise floor

Frequency Offset Mode (Option 080)

- Sets different frequency range for the source and receivers.
- Can be used for harmonics or intermodulation distortion (IMD) measurements with the VNA.

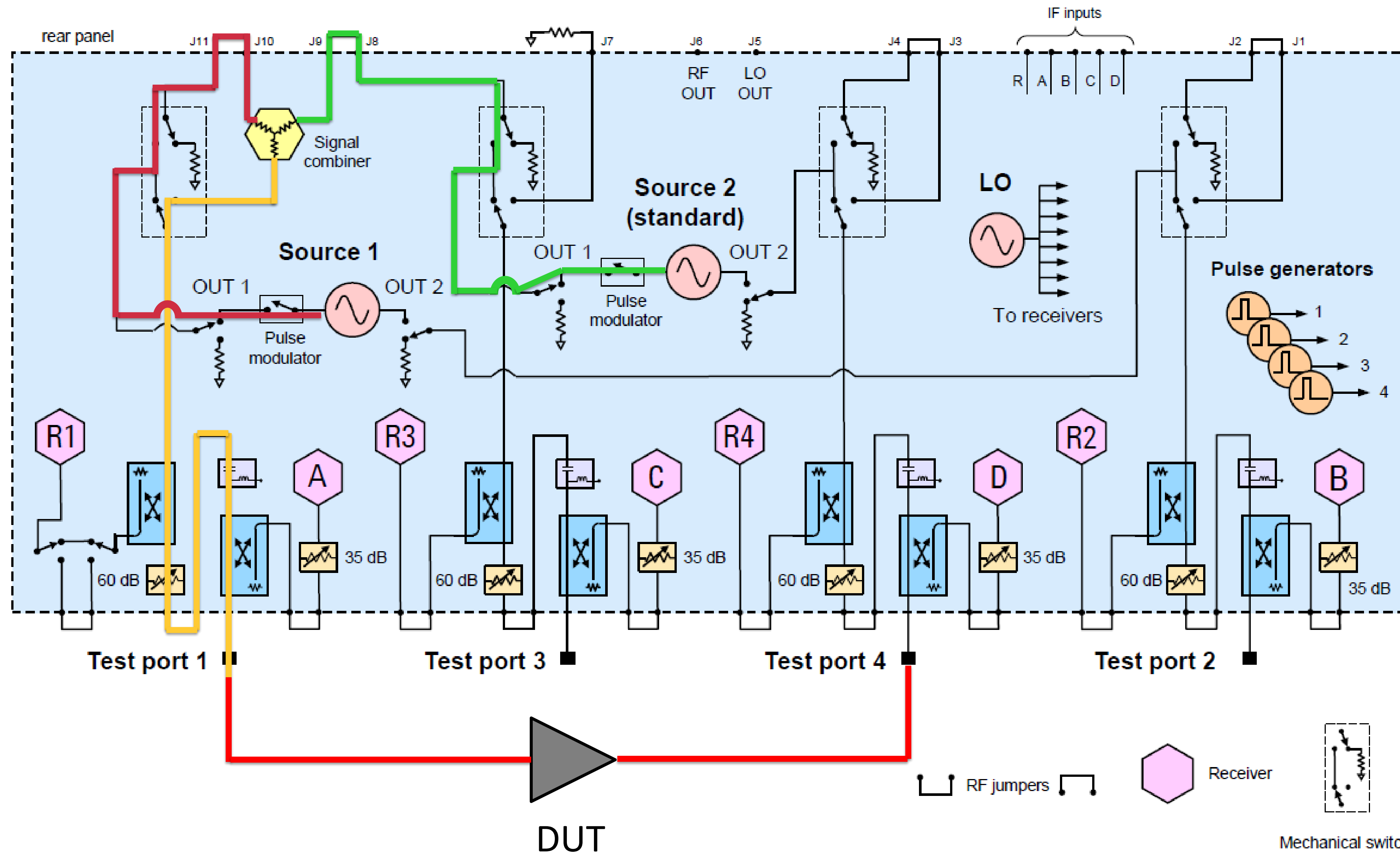
Combiner (Option 423)

- Sets different frequency range for the source and receivers.
- Can be used for harmonics or intermodulation distortion (IMD) measurements with the VNA.



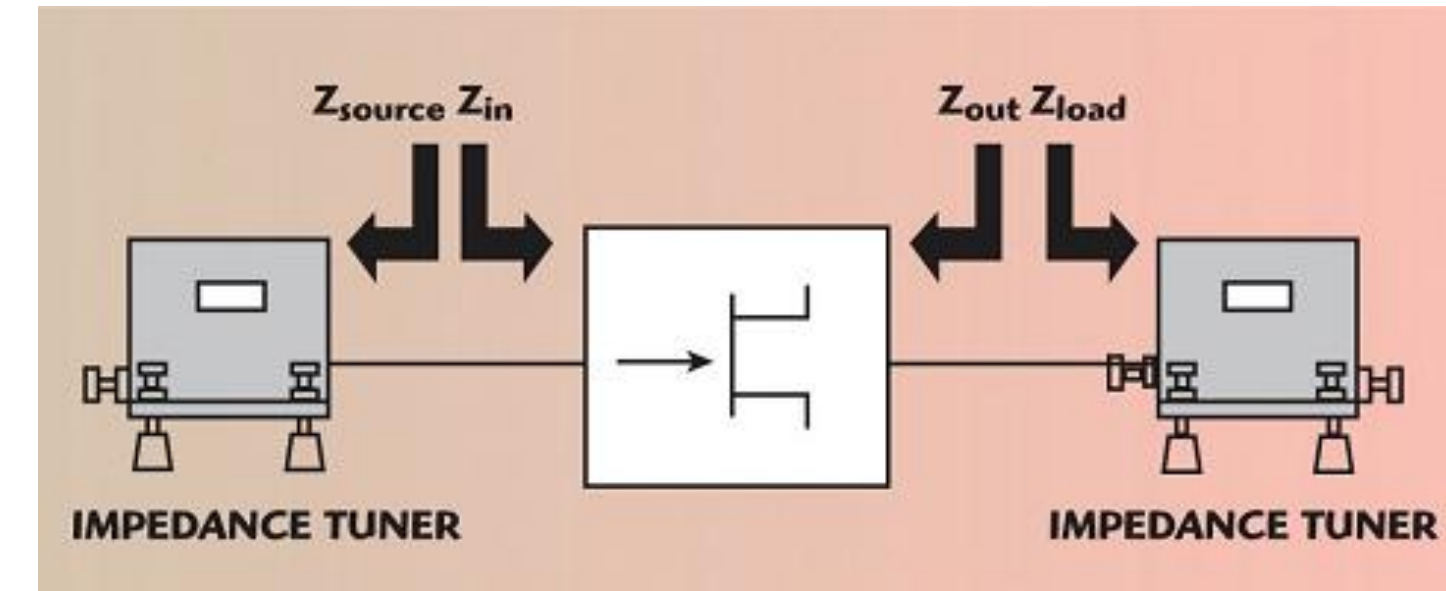
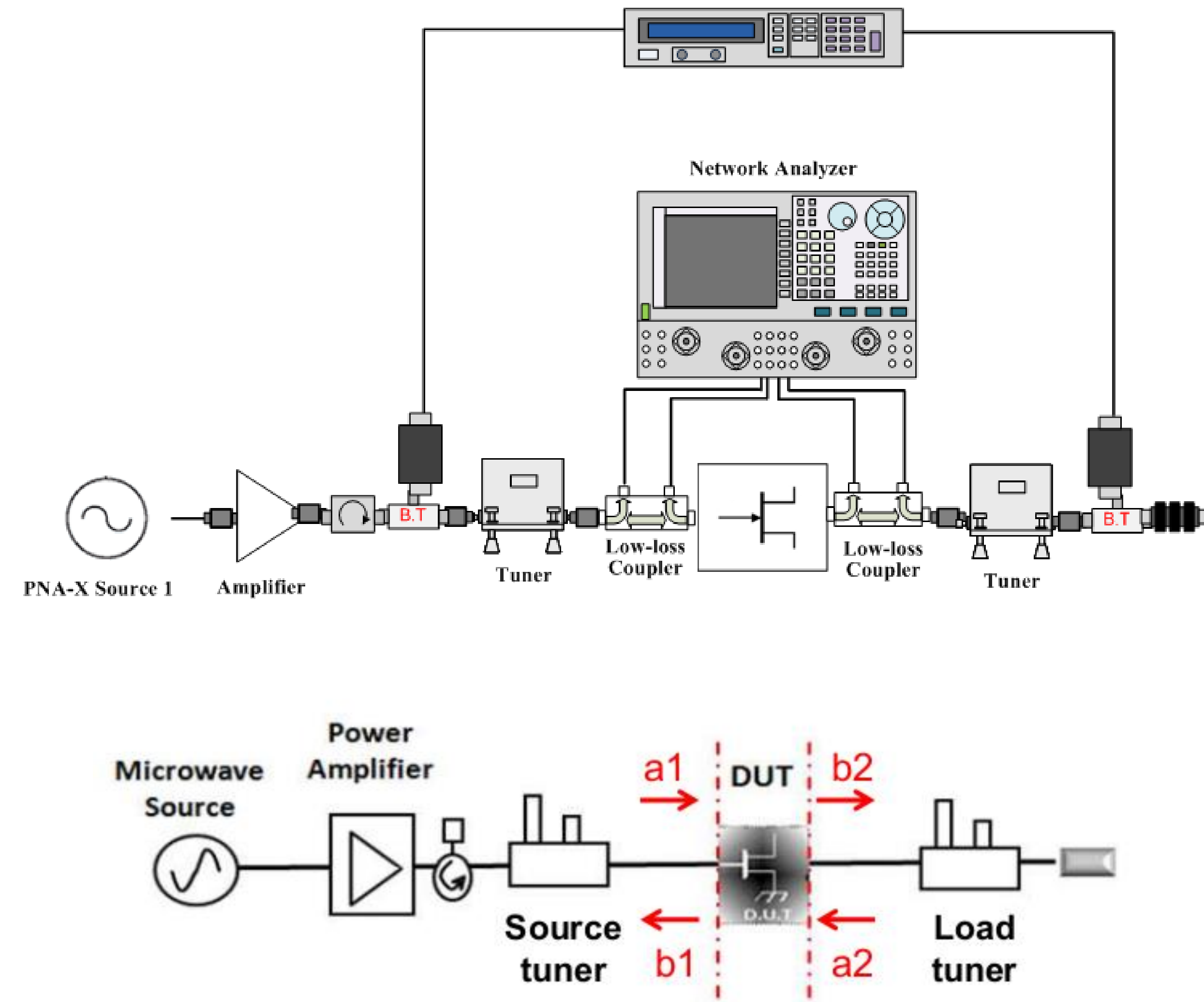
●●●● block diagram of 4 port PNAX with combiner for 2 tones

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●●●● Better loadpull structure based on VNA advanced architecture

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$$\Gamma_{in} = \frac{b_1}{a_1}$$

$$\Gamma_{load} = \frac{a_2}{b_2}$$

$$P_{out} = \frac{1}{2} (|b_2|^2 - |a_2|^2)$$

$$P_{in,del} = \frac{1}{2} (|a_1|^2 - |b_1|^2)$$

$$P_{in,available} = P_{in,del} / \left(1 - \left| \frac{Z_{in} - Z_s^*}{Z_{in} + Z_s^*} \right|^2 \right)$$

$$G_p = \frac{P_{out}}{P_{in,del}} = \frac{|b_2|^2 * (1 - |\Gamma_{load}|^2)}{|a_1|^2 * (1 - |\Gamma_{in}|^2)}$$

$$PAE = \frac{P_{out} - P_{in,del}}{P_{DC}}$$

➤ VNA based loadpull / ➤ Vector Receiver loadpull / ➤ Real Time loadpull

- *Tuner calibration*
-> *much lower density needed compared with traditional one.*
- *Receiver vector calibration*
-> *fast, not sensitive to source and load match.*
- *Receiver power calibration*
-> *absolute power cal. of receiver by power meter*

- *Integrated and fast solution*

frequency offset measurement mode for IMD3, Spectrum analyzer is not necessary

- *Reduced tuner calibration time*

real time measure mode of receiver

- *Fast tone balance leveling real-time*

power calibration is not necessary

- *Change driving PA without calibration*

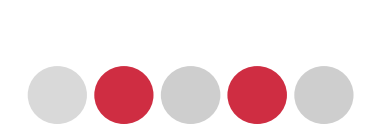
8 terms model doesn't rely on source/load match, not necessarily do raw power calibration again even change driving PA

- *PNAX should be occupied always by system*

- *PA linearity is prerequisite for accurate device linearity measurement*

The challenge of 2 tone test on unmatched device



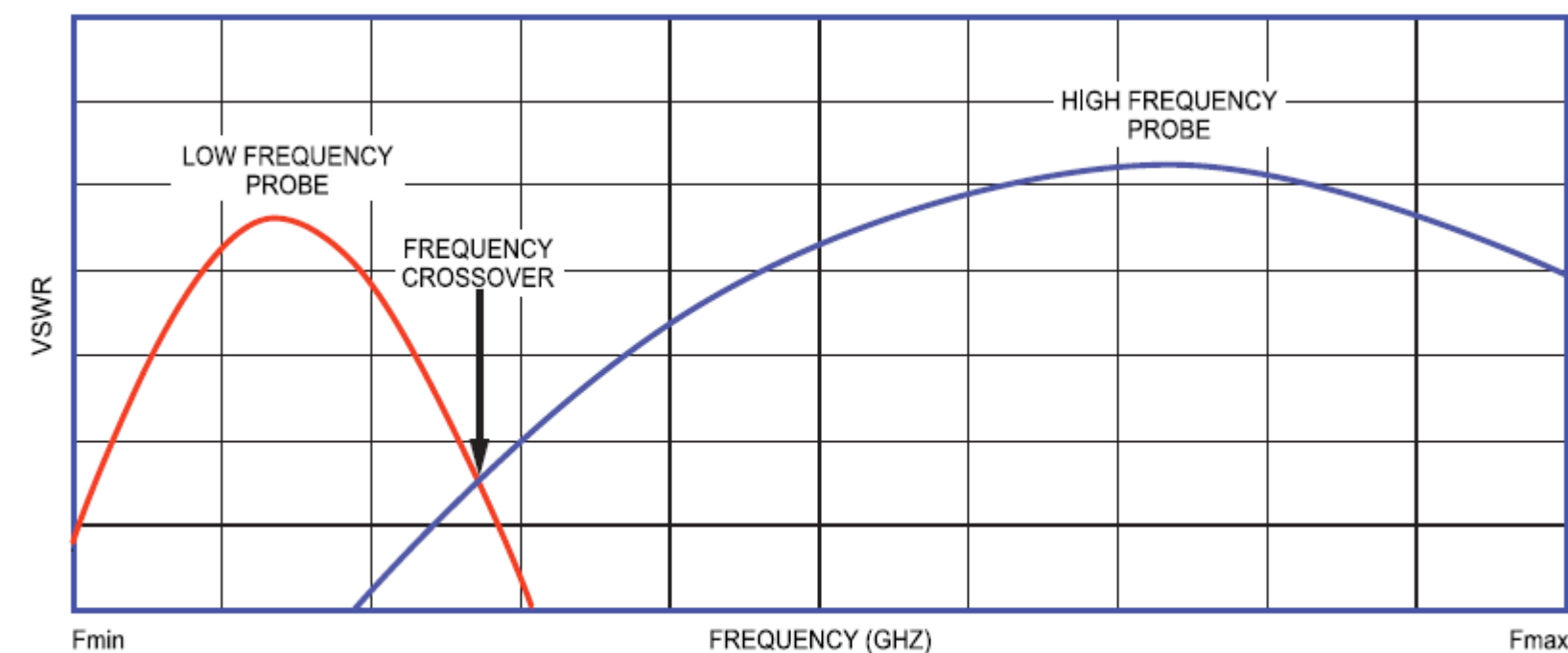
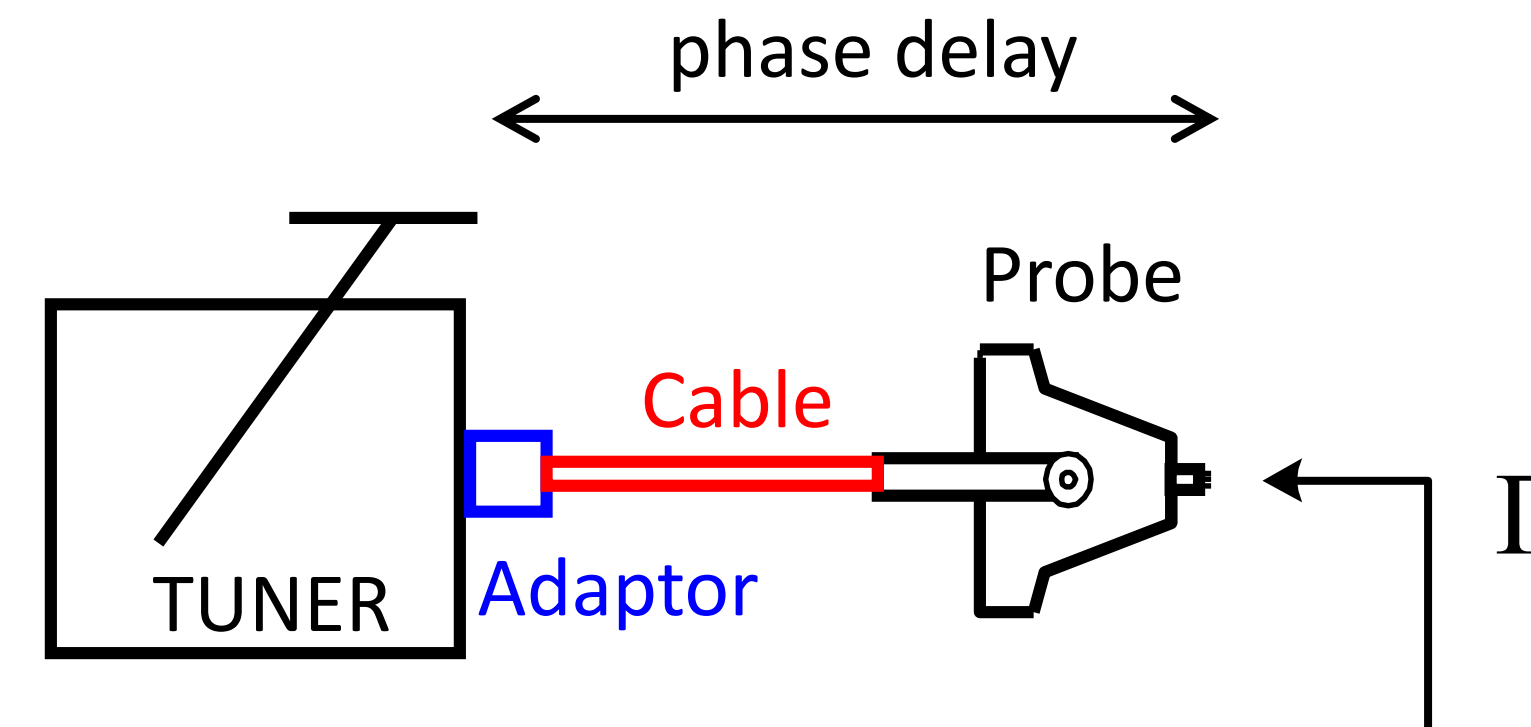
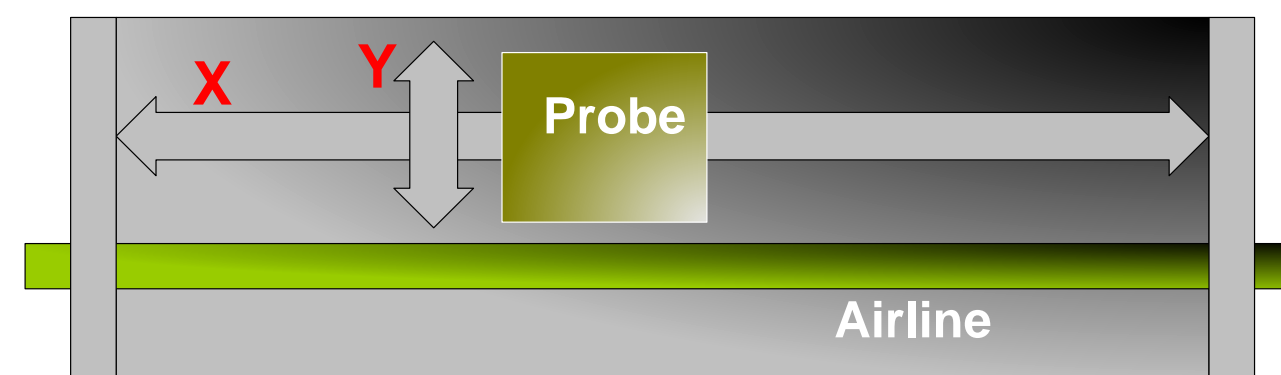


Challenge in the non 50Ohm linearity measurement

| Modulation | Freq. range | Bandwidth (single channel) | Total Bandwidth (1 Channel + ACLR) |
|---------------------|------------------|-------------------------------|---------------------------------------|
| W-CDMA | 800 MHz –3.5 GHz | 5 MHz | 15 MHz |
| Multi-carrierW-CDMA | 800 MHz –3.5 GHz | 15 MHz | 25 MHz |
| LTE | 600 MHz –6 GHz | 20 MHz | 60 MHz |
| 802.11a/b/g | 2.4 GHz | 20 MHz | 60 MHz |
| 802.11n | 2.4 GHz, 5 GHz | 40 MHz | 160 MHz |
| LTE-A | 800 MHz –3.5 GHz | 100 MHz | 300 MHz |
| 802.11ac | 5 GHz | 160 MHz | 480 MHz |
| 5G | 600 MHz –6 GHz | 100 MHz | 300 MHz |
| 5G | 28 GHz | ~1 GHz | |
| 5G | 38 GHz | ~1 GHz | |

Bandwidth is more than 40 MHz in 4G times, it will be much wider in the coming 5G times, what are the challenges for linearity non-50 load pull test for PA?

Phase shift issue



VSWR versus Frequency of a two-probe slide-screw tuner.

For passive tuner, where there is distance of probe to DUT, there will be phase shift, longer the distance, greater the phase shift

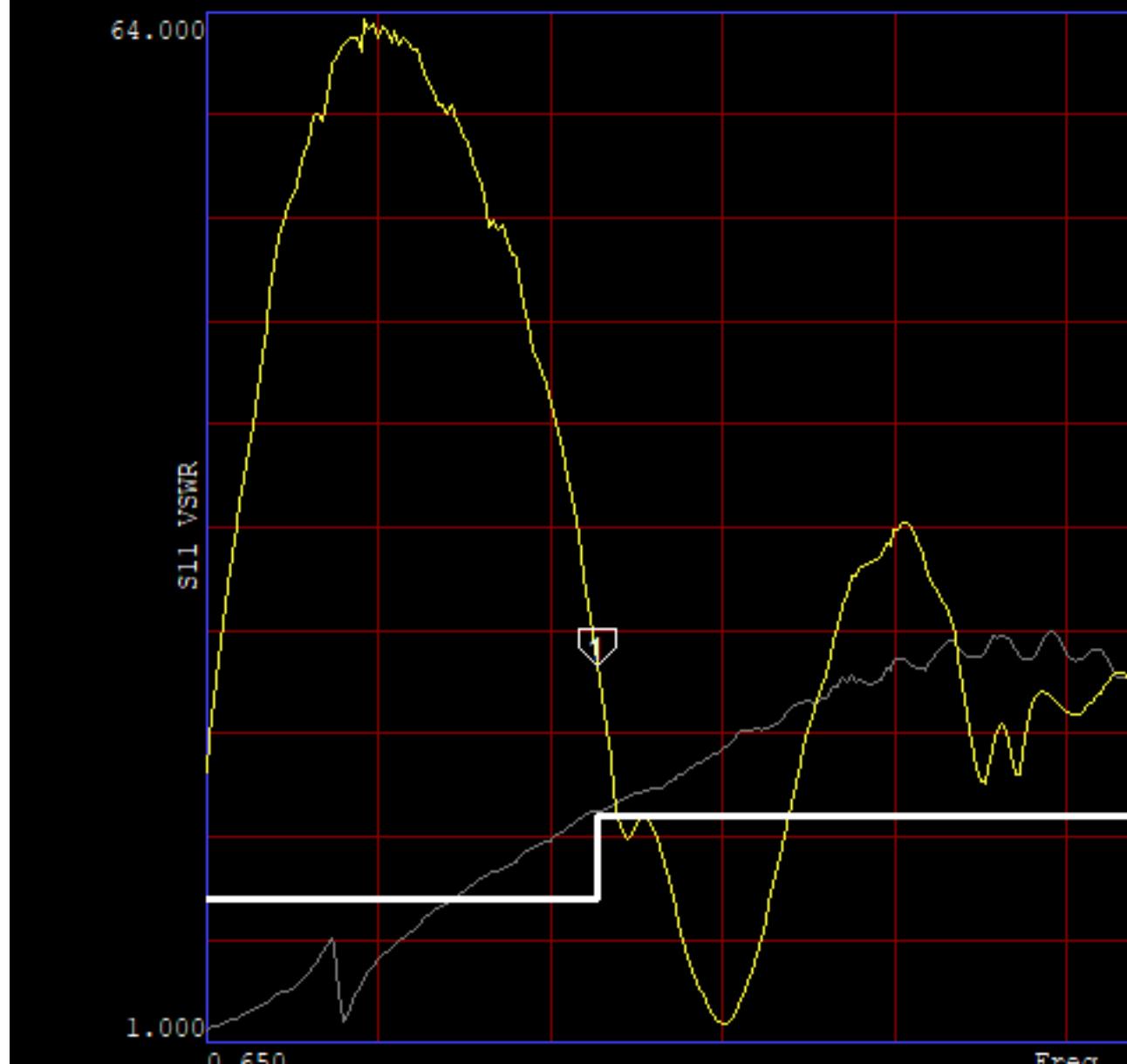
The great phase shift is not the same in the real matching network

Tuner matching frequency response of a typical position

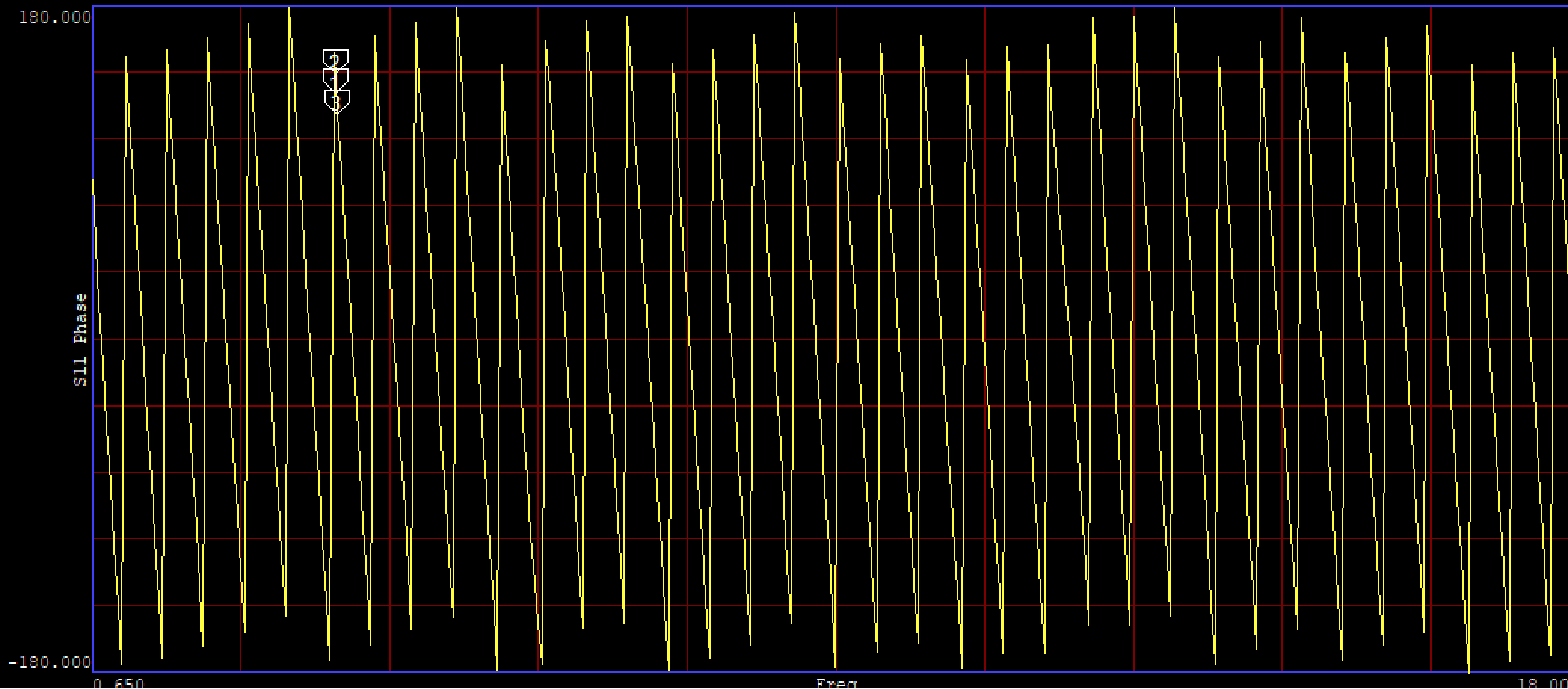
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782942 MT982GL01 5979 PL HFP, C=100 11 29 2017
782942 MT982GL01 5979 PL LFP, C=100 11 29 2017
Marker 1: Freq = 4.600 GHz, S11 VSWR = 24.2167

Model: MT982GL01, 0.65-18GHz, crossover freq.: 4.6GHz
Position: carriage, probe1, probe2: (100, 0, 5000)



782942 MT982GL01 5979 PL LFP, C=100 11 29 2017
Marker 1: Freq = 3.500 GHz, S11 Phase = 132.7817 Deg
Marker 2: Freq = 3.485 GHz, S11 Phase = 143.8944 Deg
Marker 3: Freq = 3.515 GHz, S11 Phase = 121.6763 Deg



Tuner is a **very narrow** freq. response device which is not optimum for wideband measurement

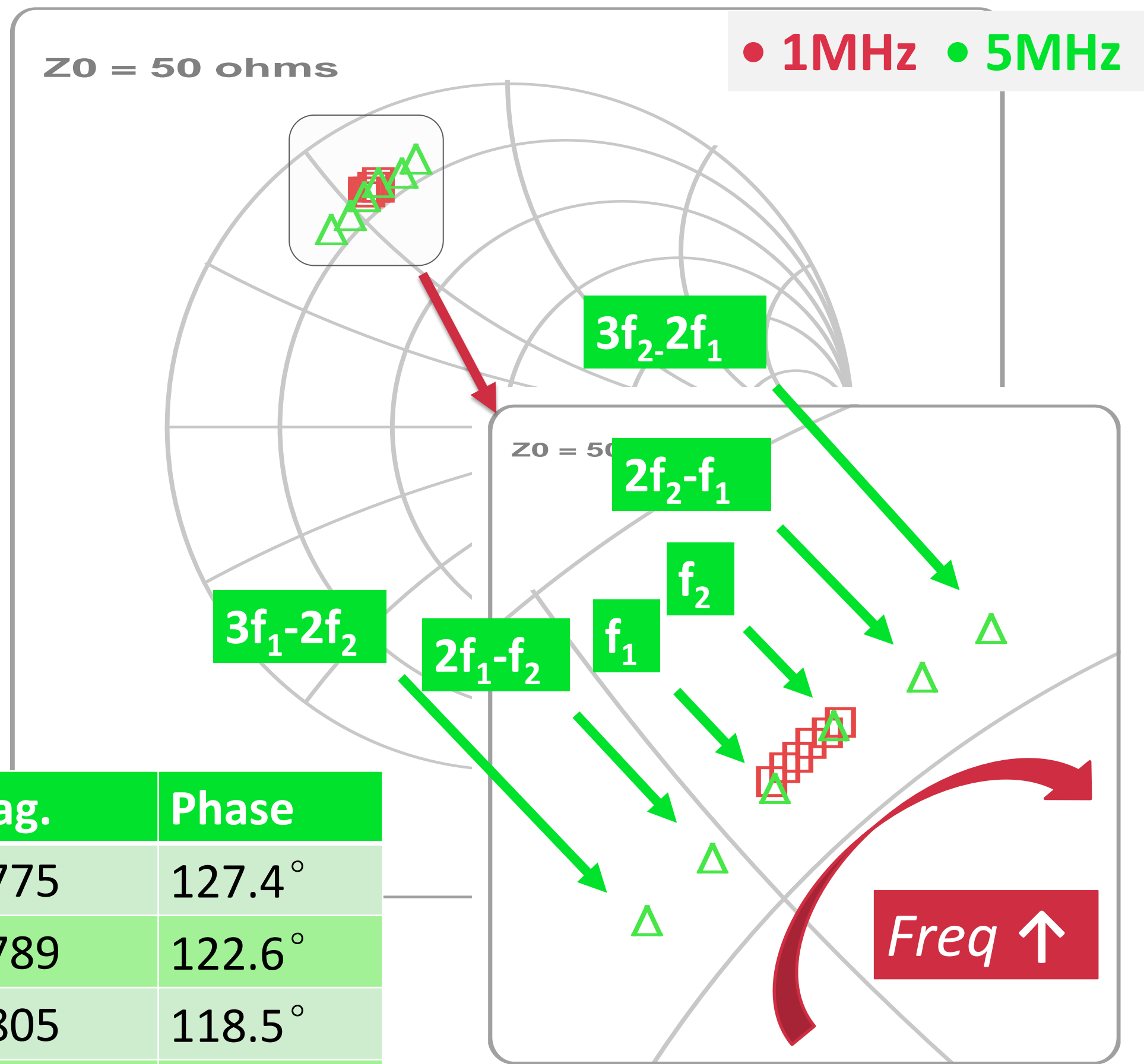
Narrow response issue

Summary of the challenges, NO. 1, phase shift

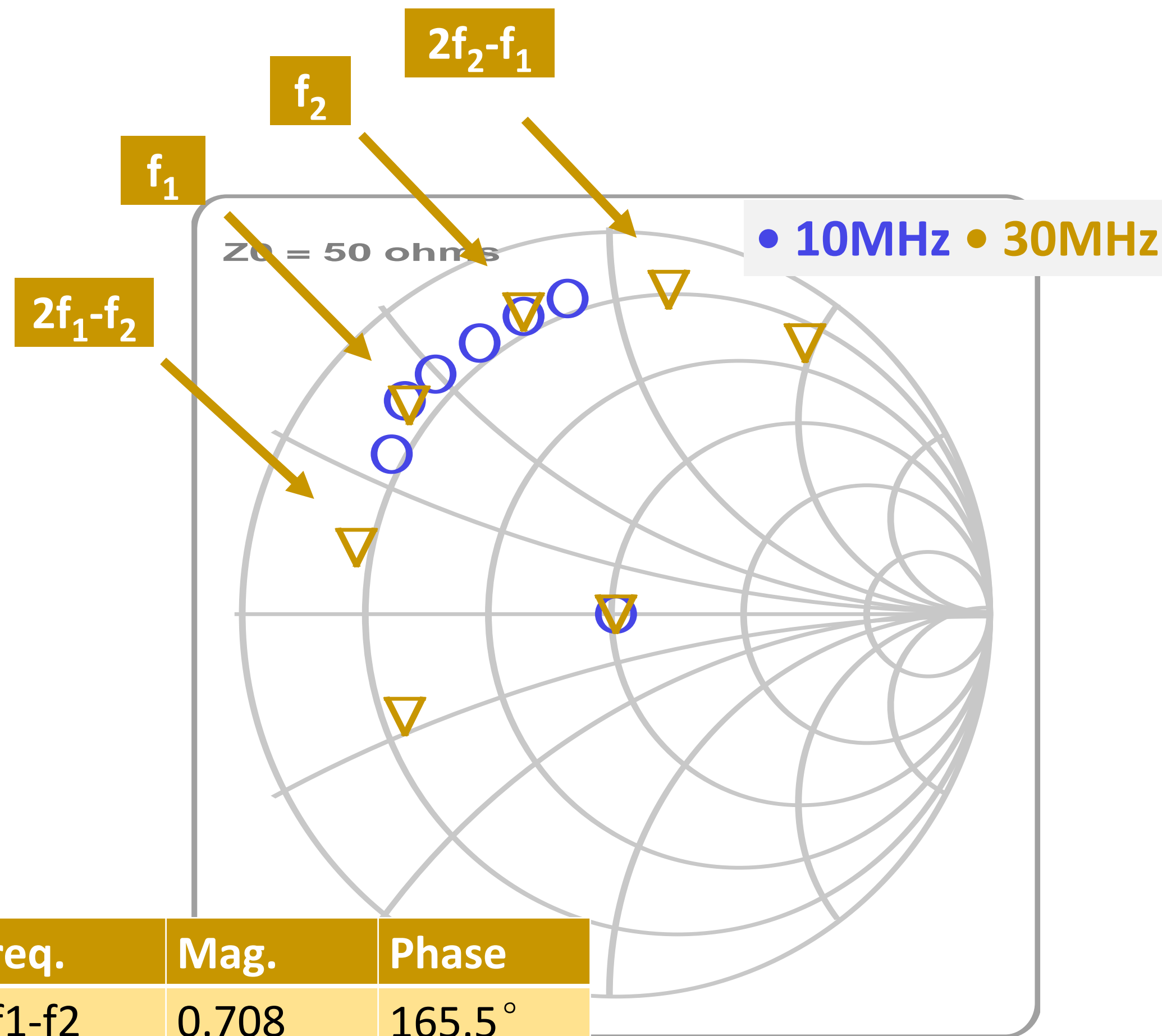
Carrier freq.: 3.5GHz

Load gamma: $0.8 \angle 120^\circ$ (carrier)

Tone space: 1, 5, 10, 30MHz



| Freq. | Mag. | Phase |
|--------------|-------|---------------|
| $2f_1 - f_2$ | 0.775 | 127.4° |
| f_1 | 0.789 | 122.6° |
| f_2 | 0.805 | 118.5° |
| $2f_2 - f_1$ | 0.807 | 113.3° |



| Freq. | Mag. | Phase |
|--------------|-------|---------------|
| $2f_1 - f_2$ | 0.708 | 165.5° |
| f_1 | 0.770 | 134.4° |
| f_2 | 0.824 | 106.7° |
| $2f_2 - f_1$ | 0.859 | 80.18° |

Summary of the challenge , No. 2, system non-linearity

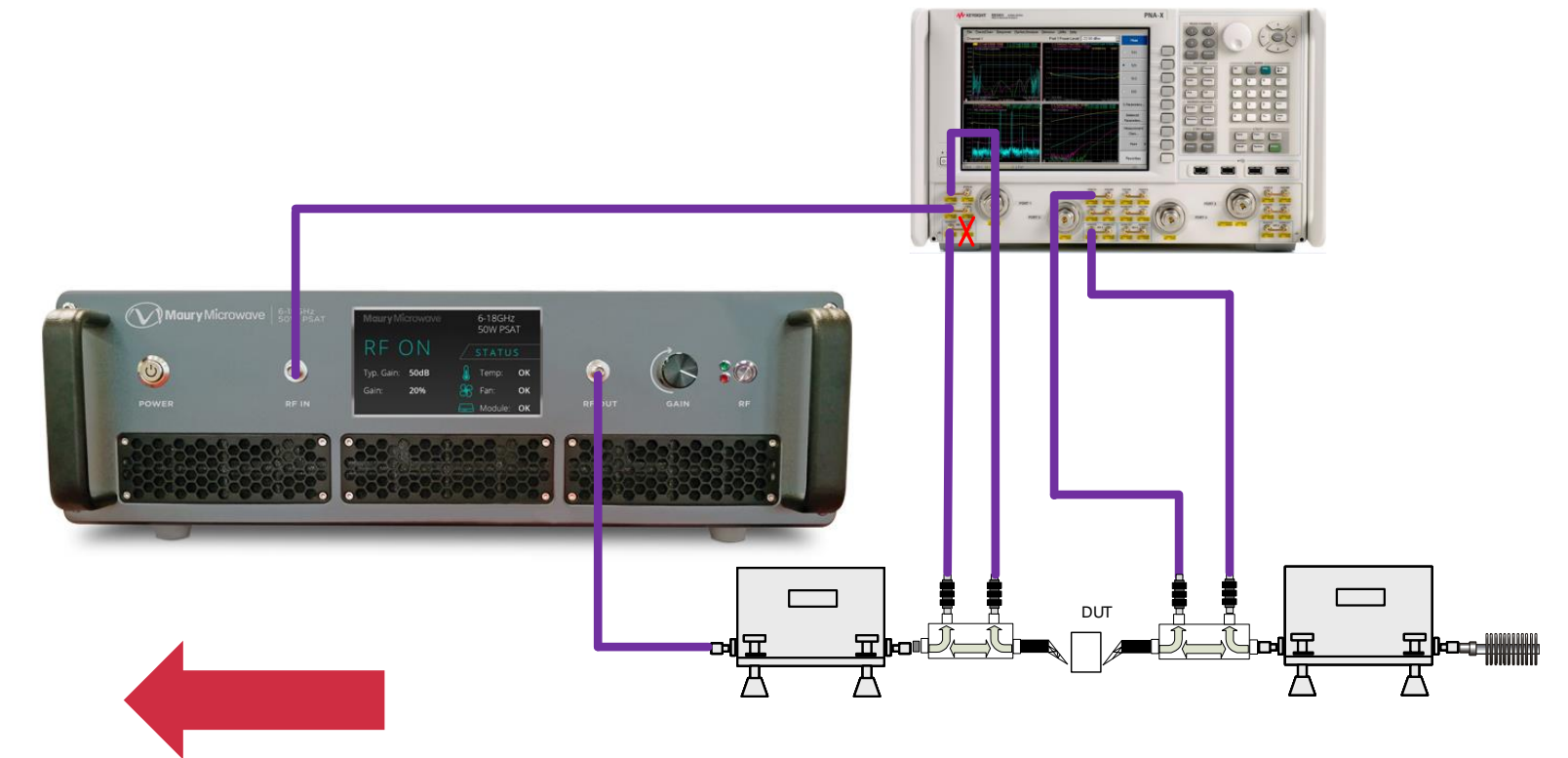
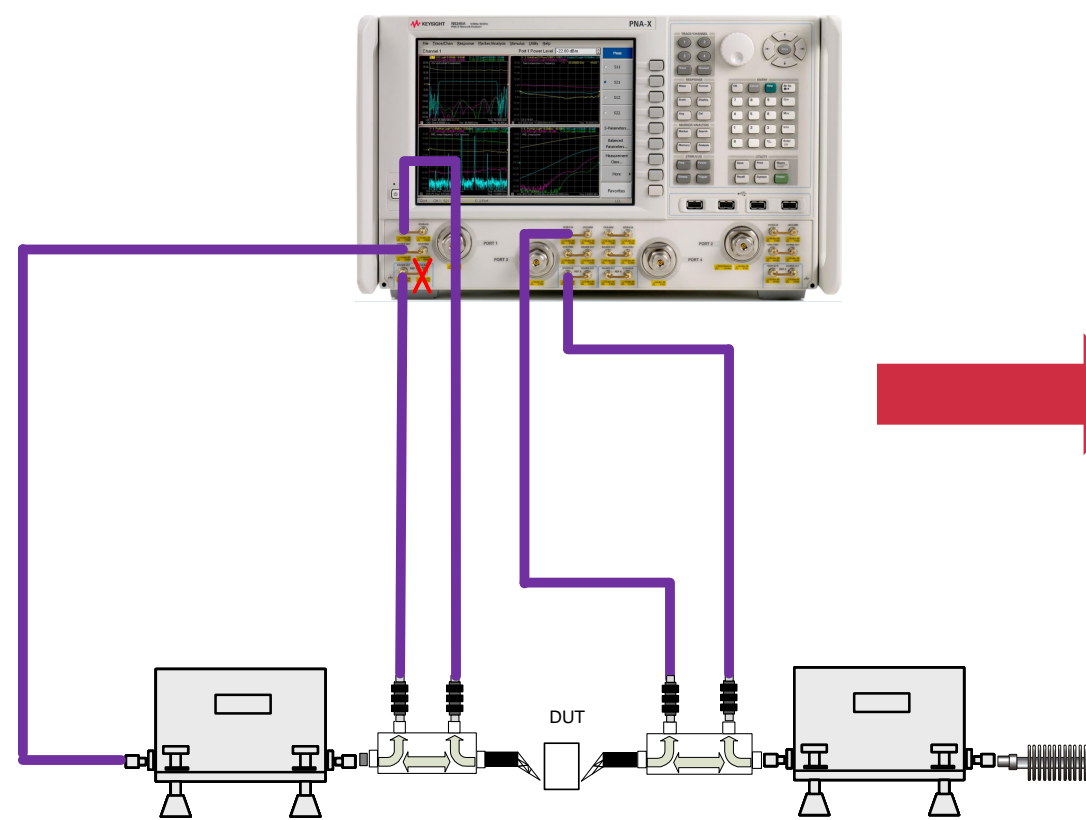
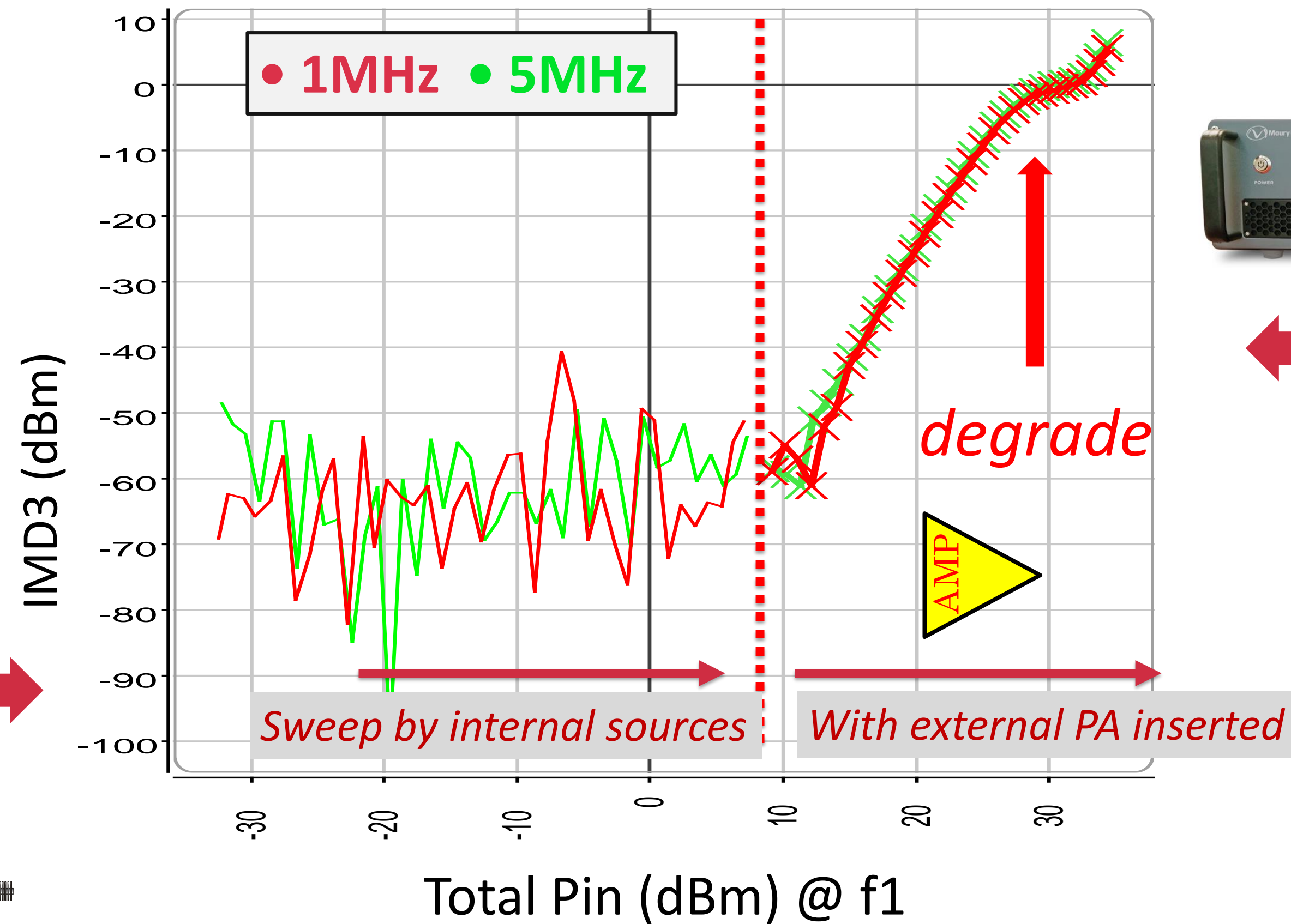
20

Carrier freq: 3.5GHz

Load gamma: $0.8 < 120^\circ$ (carrier)

Tone space: 1, 5, (10, 30)MHz

IMD3 (dBm) vs. Total Pin(dBm)

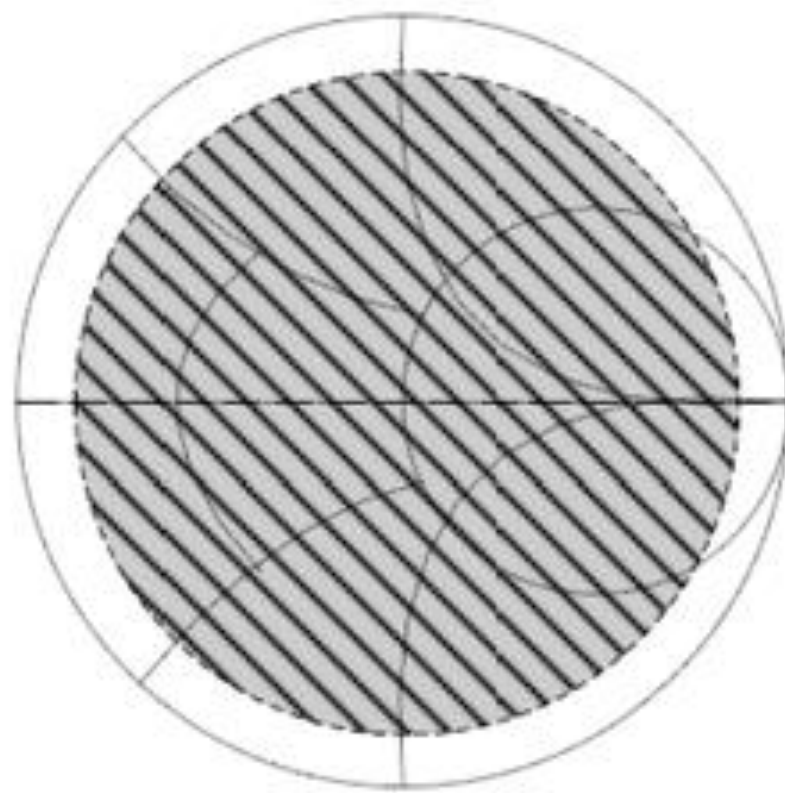


Summary of the challenges, NO. 3, limited matching range

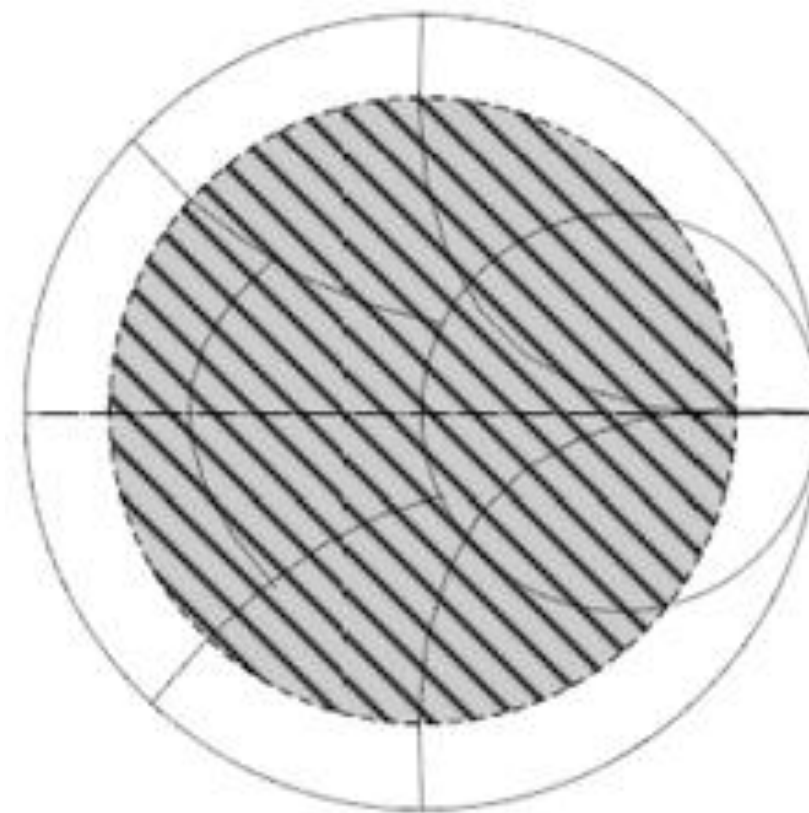
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Shrunked tuning range, inevitable, insoluble by passive tuner itself

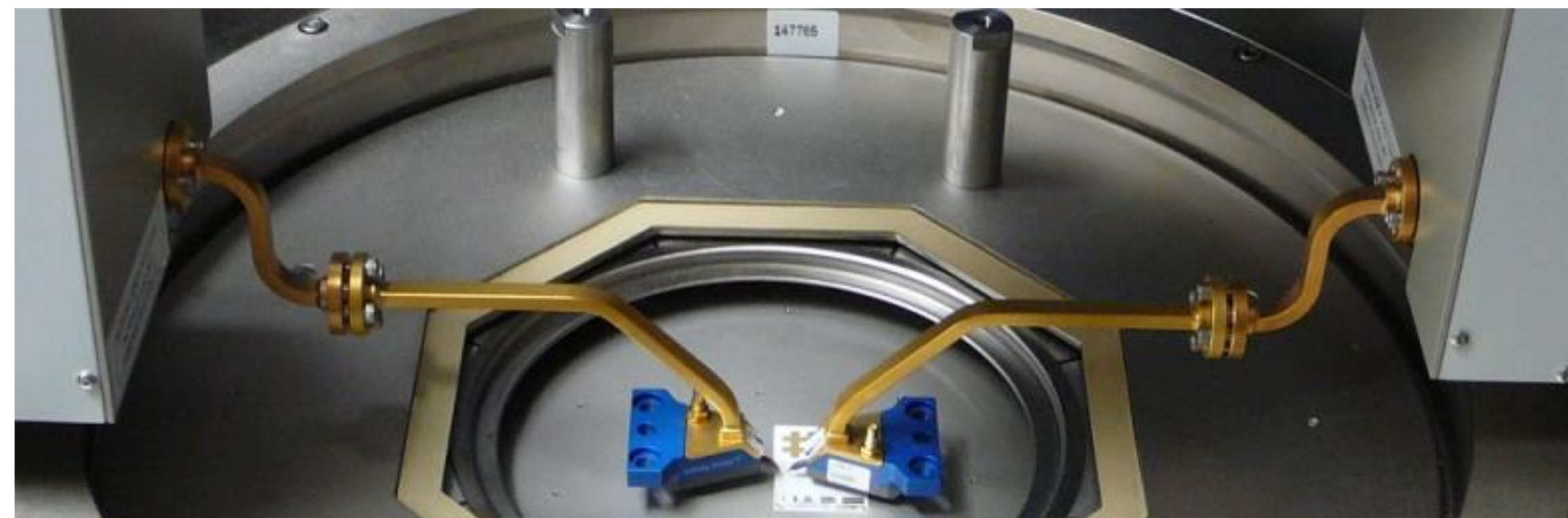
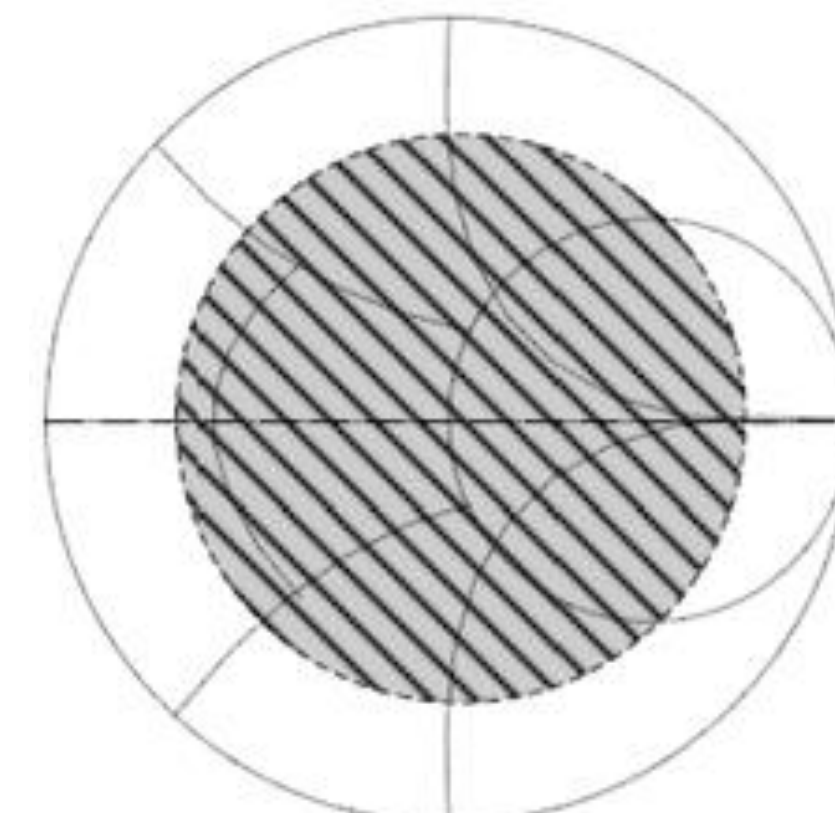
Tuner plane



Coaxial/Waveguide plane



Probe tip plane



Greatly subject to loss between Tuner and DUT, especially on wafer!

●●●● Common issues of the passive 2 tones loadpull system

- *Tedious tuner calibration*
- *Limited matching range due to passive tuner*
- *2 independent highly-linear sources with combiner, spectrum analyzer and VNA configurable test set option are **not cheap***
- ***Tone balancing** is necessary which limits the speed*
- *Accurate linearity measurement relies on the **linearity of source and amplifier***

A novel 2 tone measurement solution → MT2000!



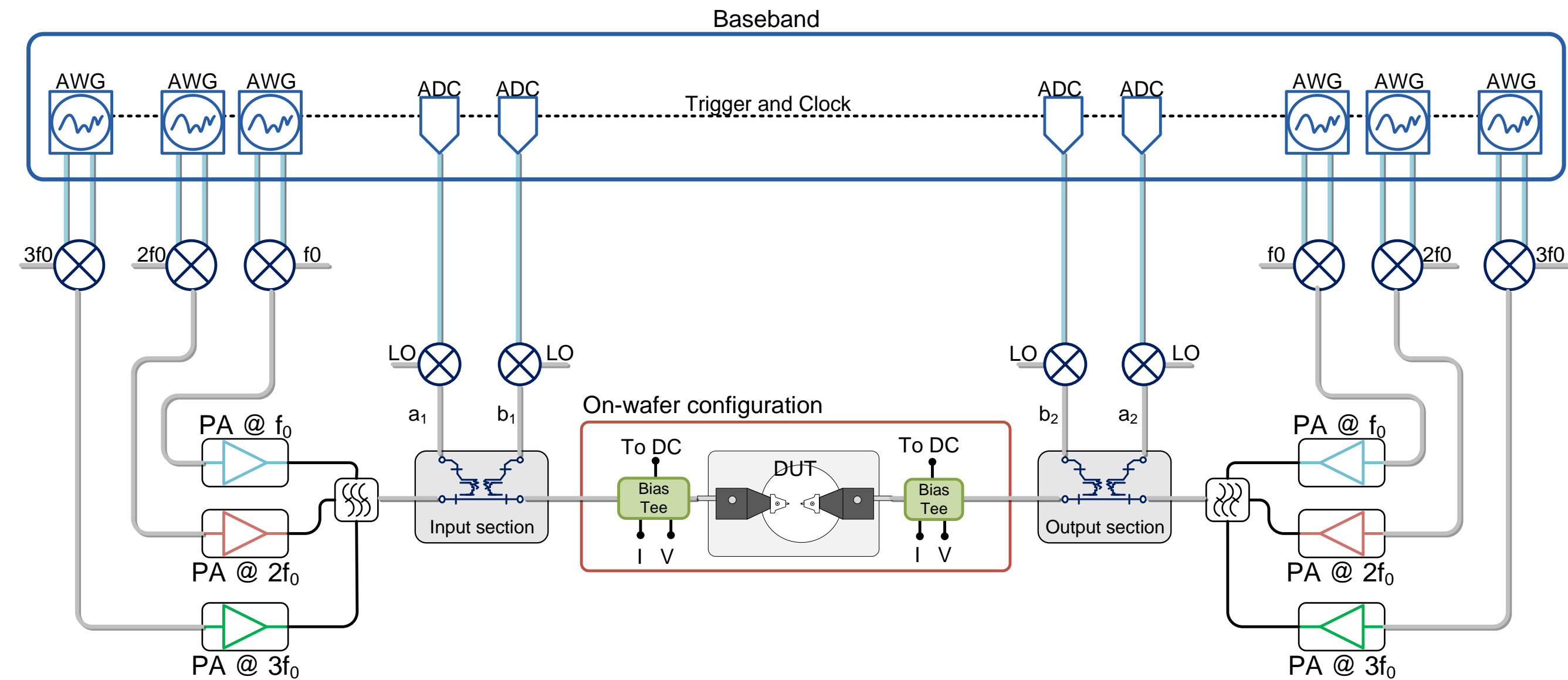
A brand-new architecture for wideband loadpull

- *Baseband signal generation including 2 tone*
- *Specific receiver covers both small and large signal measurement*
- *DPD similar algorithm for non linearity minimization of source or even driving amplifier*
- *Ultra-broadband tone spacing supported up to 166MHz or wider*
- *Ultrafast system calibration and measurement, order of few minutes*

System architecture

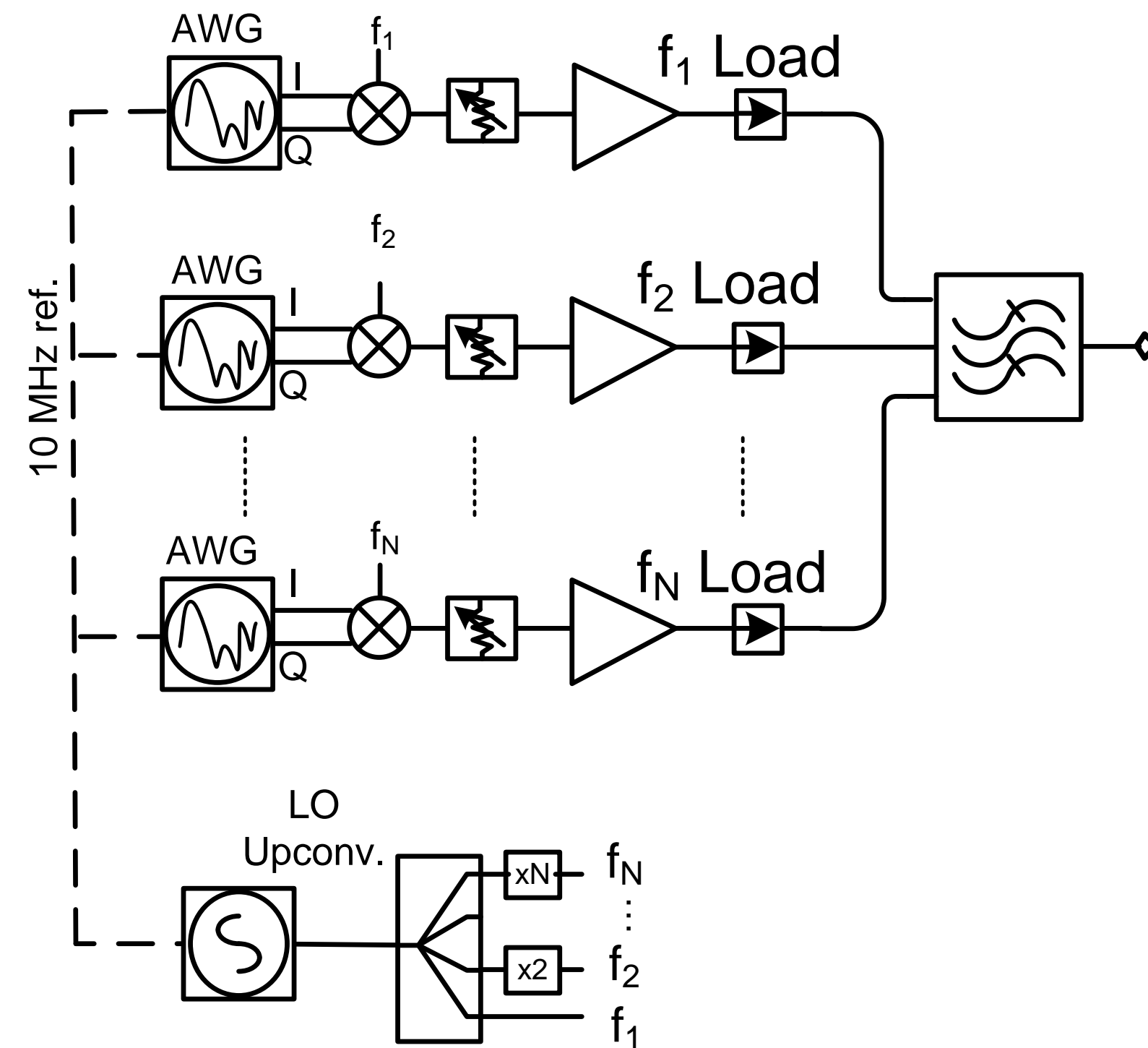
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MT1000/MT2000 architecture combines traditional analog and microwave techniques with low-frequency signal acquisition (A/D converters) and generation (Wideband AWG).



- A vector network analyzer VNA is integrated
- Two-port and power calibration to measure S-parameters and power
- Wideband ADCs allow measurement of wideband signals (power, ACPR, EVM)
- System includes up to 6 VSGs to generate custom modulations up to 500 MHz bandwidth
- Each VSG can be used as an active tuner

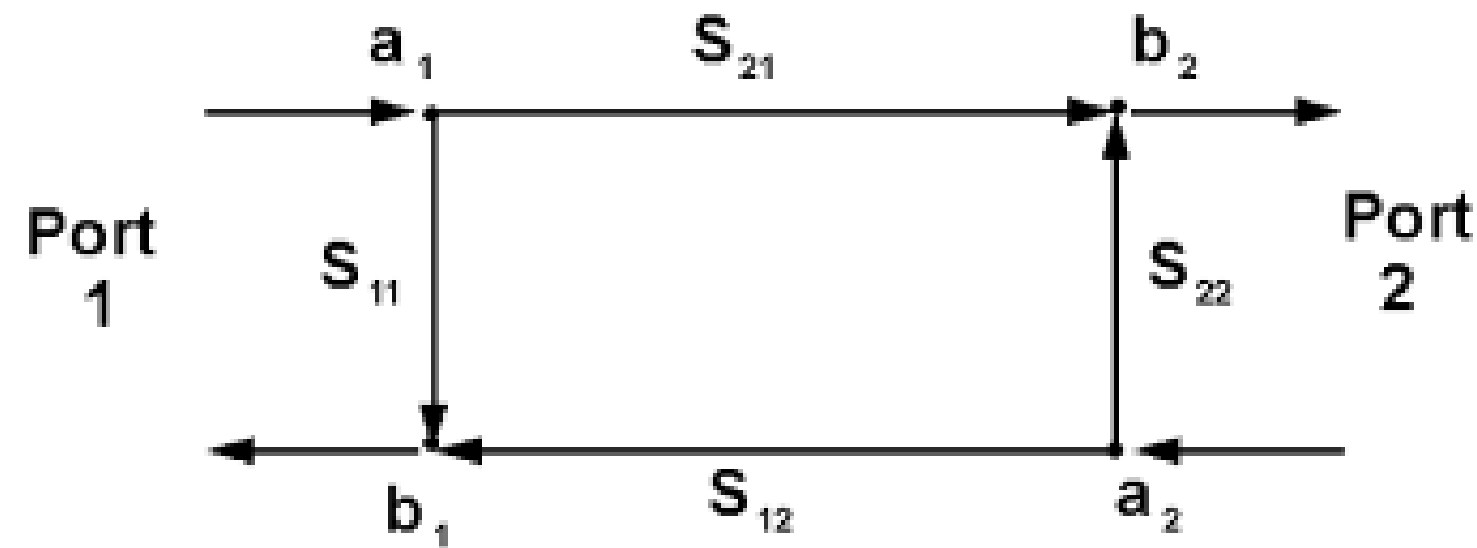
How does it work?



- *Test signals are generated in the time-domain at low frequency with AWGs*
- *Single local oscillator (LO) up-converts the waveforms at fundamental and harmonic frequencies by means of multipliers to guarantee phase coherency*

●●●● Active load for wideband impedance tuning

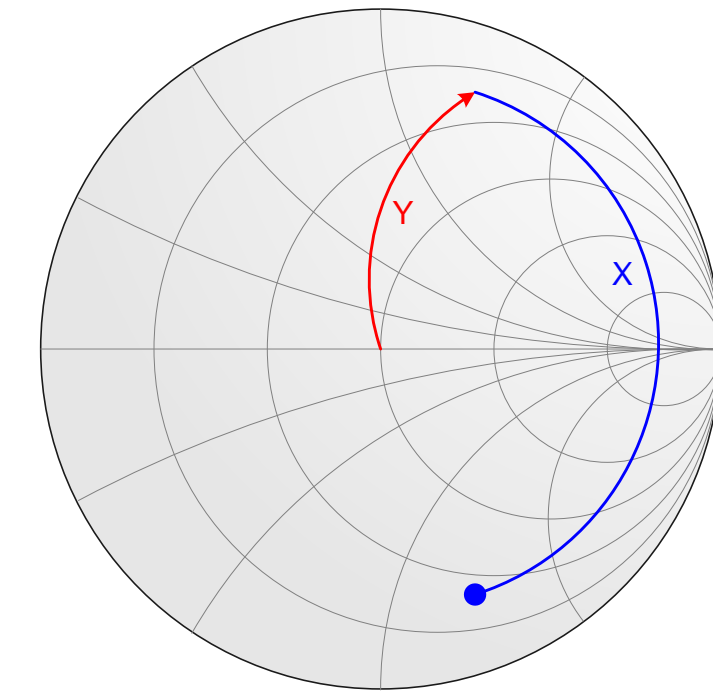
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Two-port device represented in terms of S-parameters and a-waves and b-waves

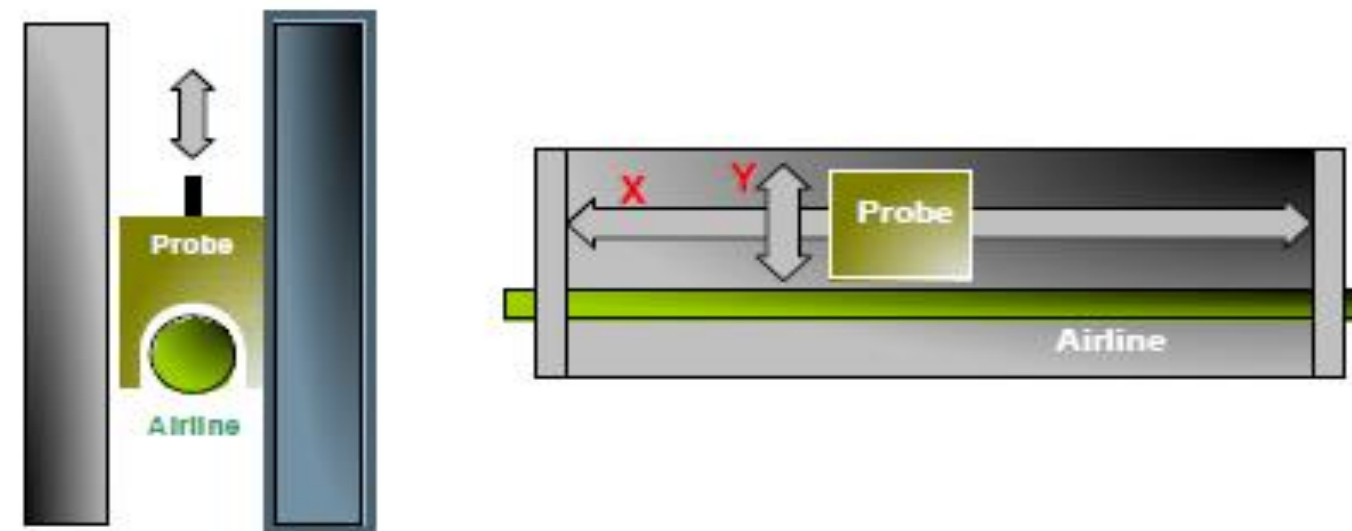
$$\Gamma_{x,n}(f_n) = \frac{a_{x,n}(f_n)}{b_{x,n}(f_n)}$$

Formula governing Gamma in relation to a-waves and b-waves



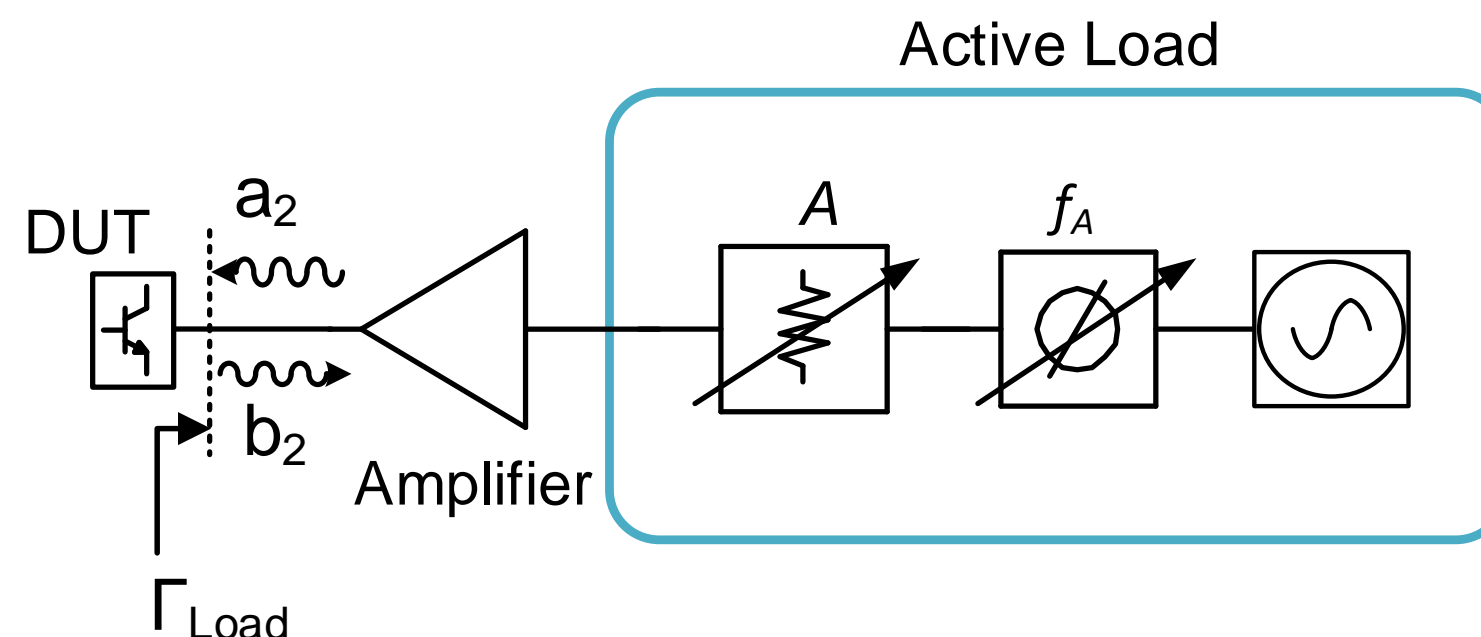
Changing magnitude and phase of b_2 will result in any impedance on Smith Chart

Passive Load Pull



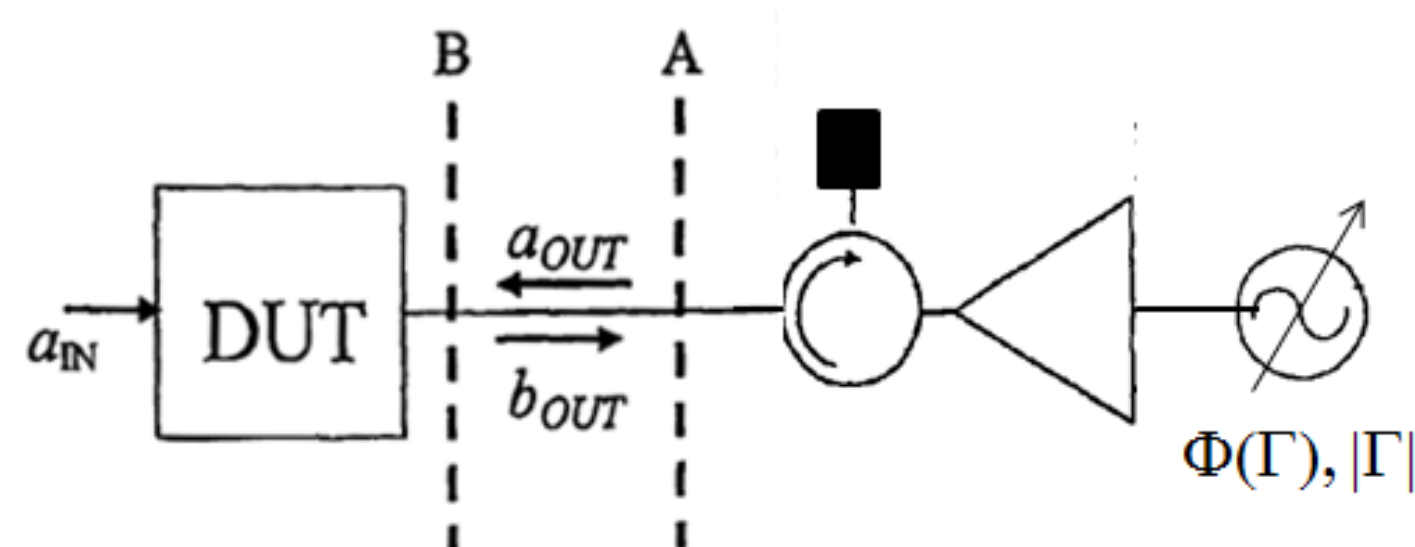
A passive mechanical tuner is used to reflect a portion of the DUT's energy b_2 back towards DUT as a_2 . The position of the probe will determine the magnitude and phase of the reflection. Γ will be lower than 1 since $a_2 < b_2$ due to losses.

Open Loop Active Load Pull



A signal generator with magnitude and phase control is used to inject a new signal a_2 into the output of the DUT. Γ can be equal or greater than 1 since a_2 is independent of b_2 .

Open loop active

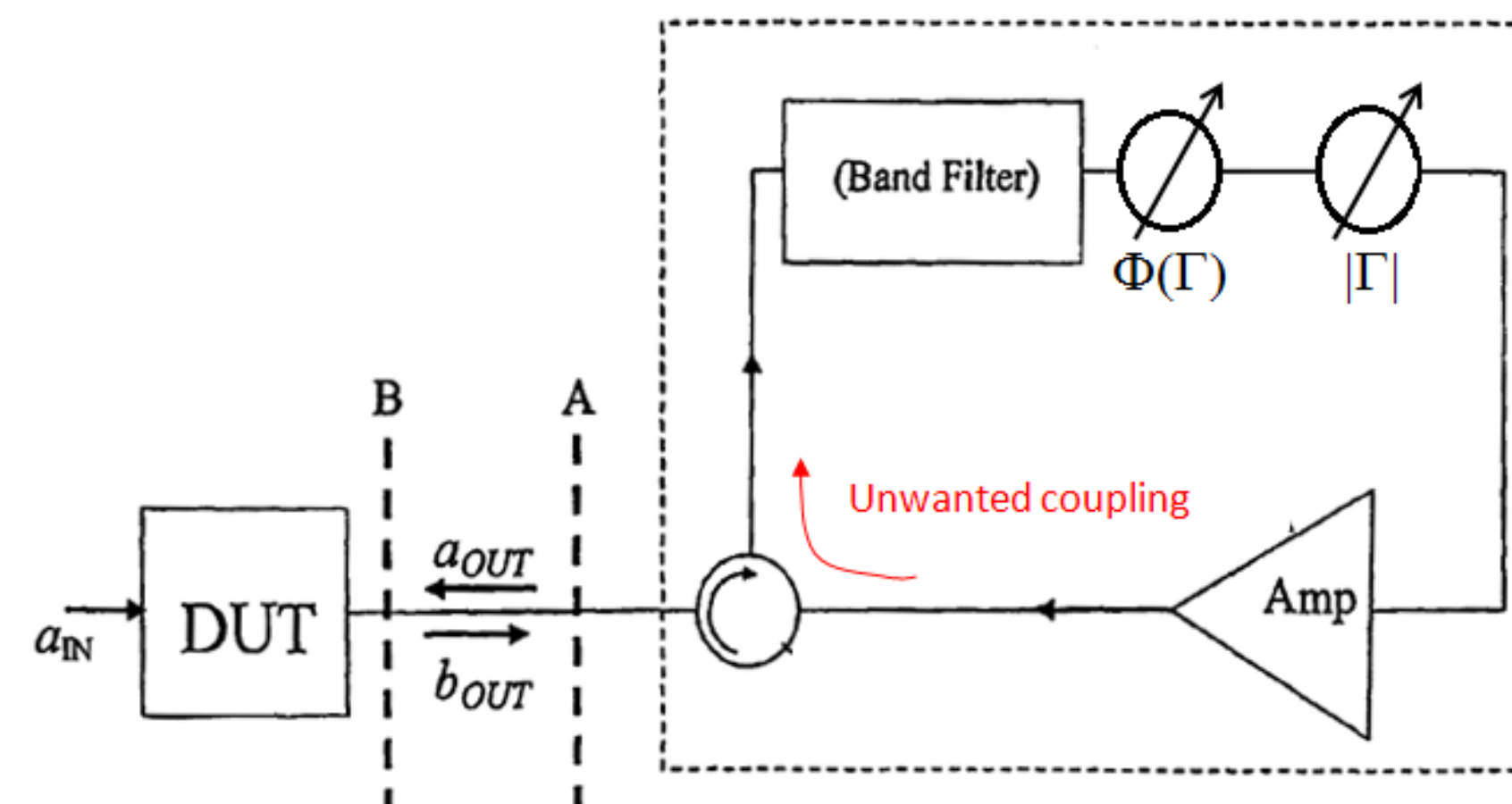


Open loop active requires custom algorithms for iterative convergence to synthesize desired reflection coefficients because the output of DUT (transmitted traveling wave, b_2) is dependent on device operating conditions

The load impedance is controlled by an RF signal provided by a load RF source. The load signal is not looped, so oscillation will never be observed (because the loop is only in the software, with an algorithm which controls the gamma)

Maury provides open loop solution!

Close loop active



the b_{OUT} signal is looped into a circuit that changes the magnitude and phase of the coupled RF signal, and this signal is then re-injected toward the DUT (a_{OUT}).

The oscillation risk is high because some unwanted coupling can take place, and this parasitic coupled signal is then amplified and phase shifted as well. Looking at this parasitic coupling path, if the magnitude reaches $|1|$, and the phase reach (180°) , then an oscillation will occur.

Wideband multi-tones arbitrary impedance tuning

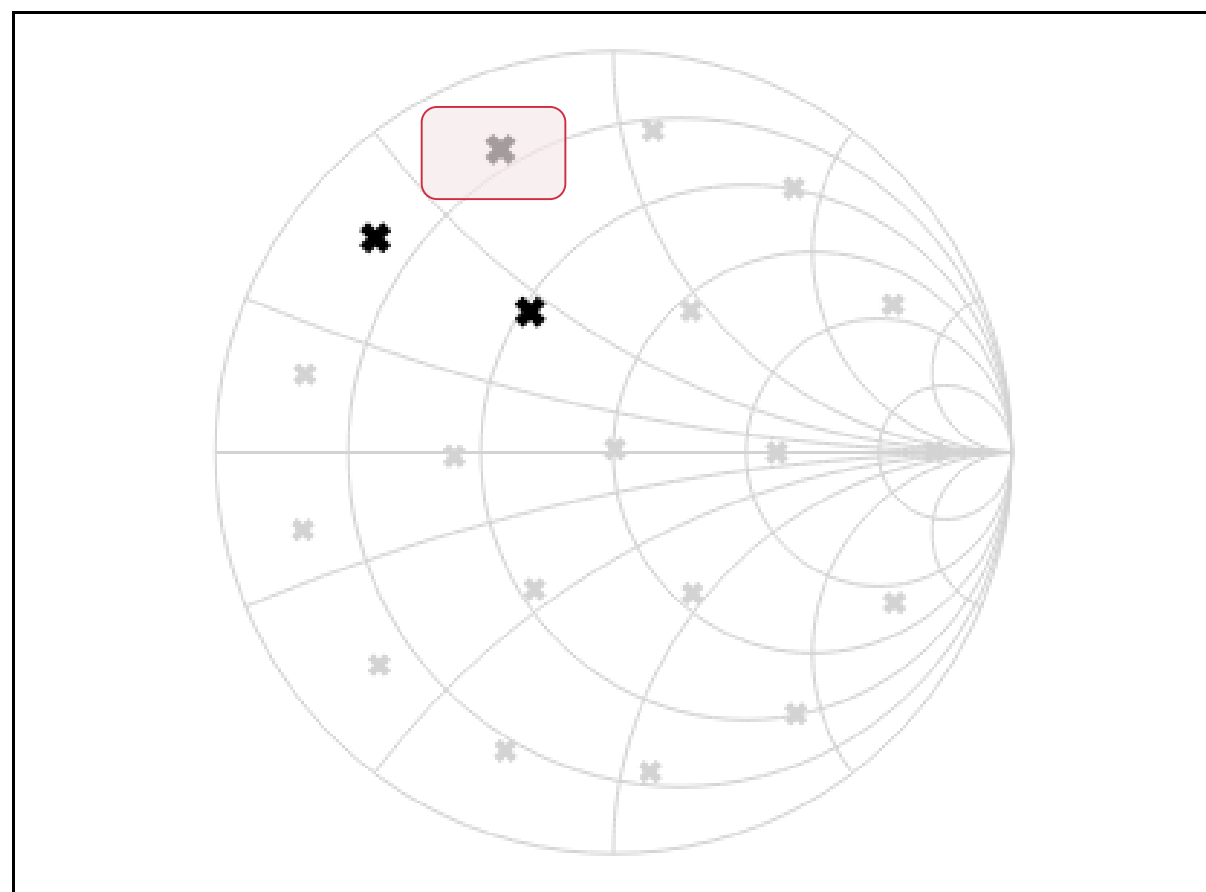
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Carrier freq: 2.6GHz

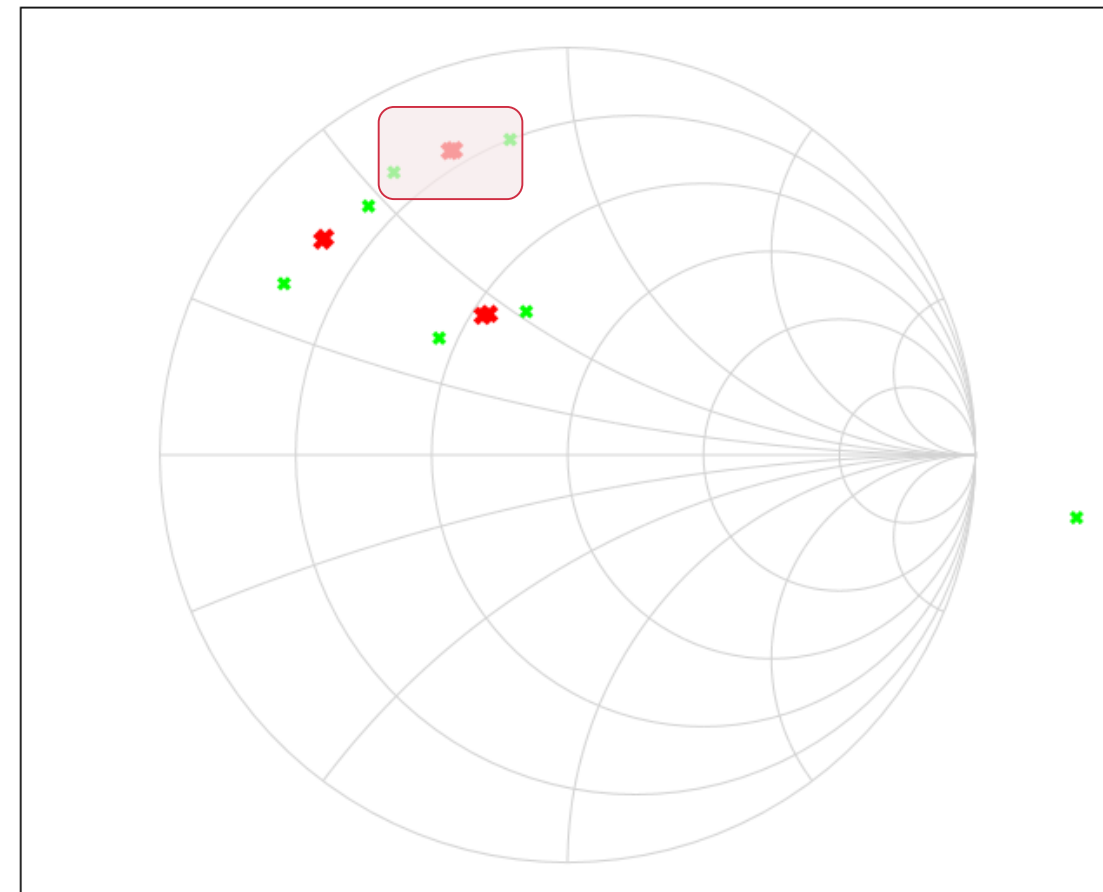
Carrier impedance: $0.8 < 110^\circ$

Tone space: 20 MHz

× termination
× passive tuning
× active tuning

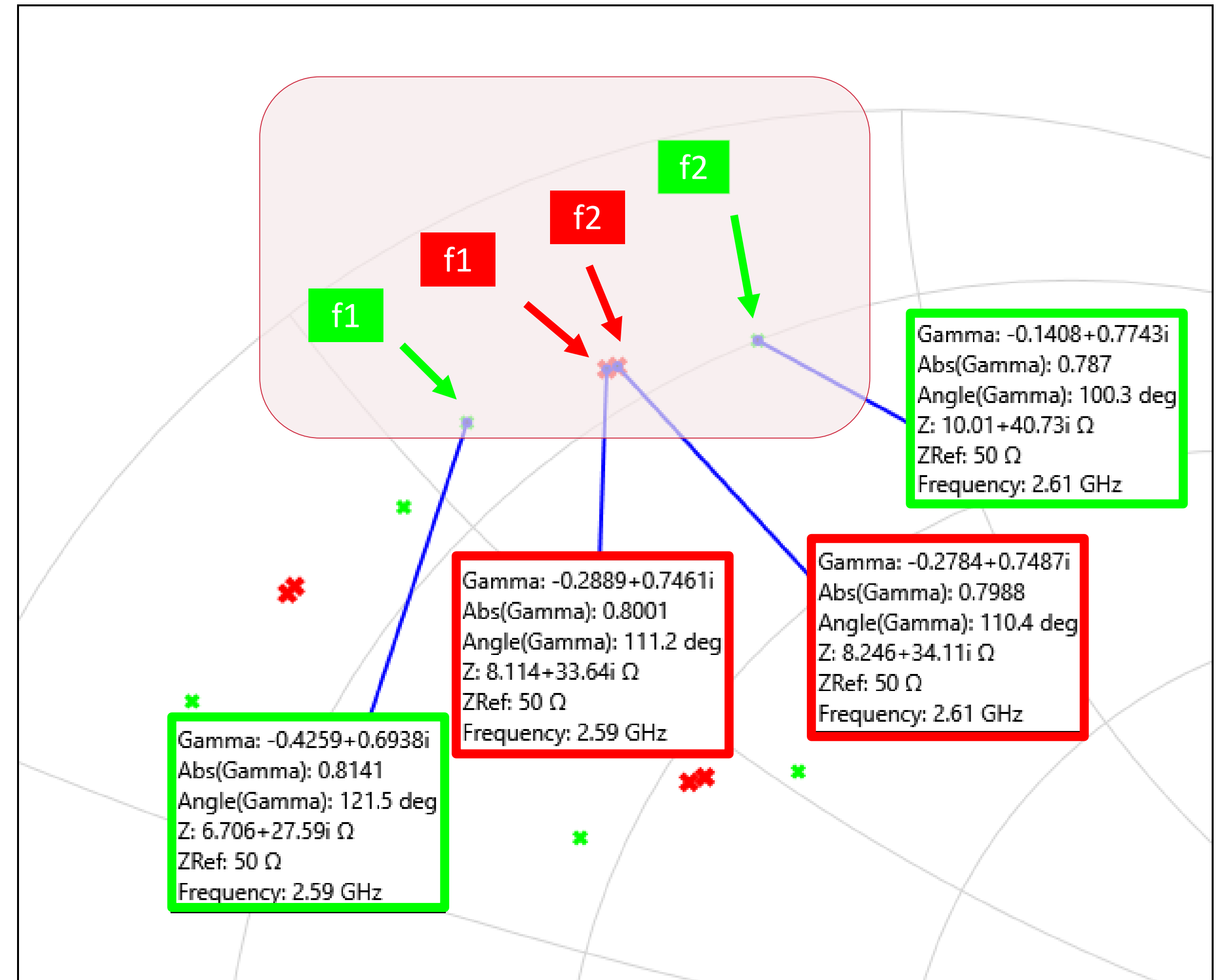


Selected termination



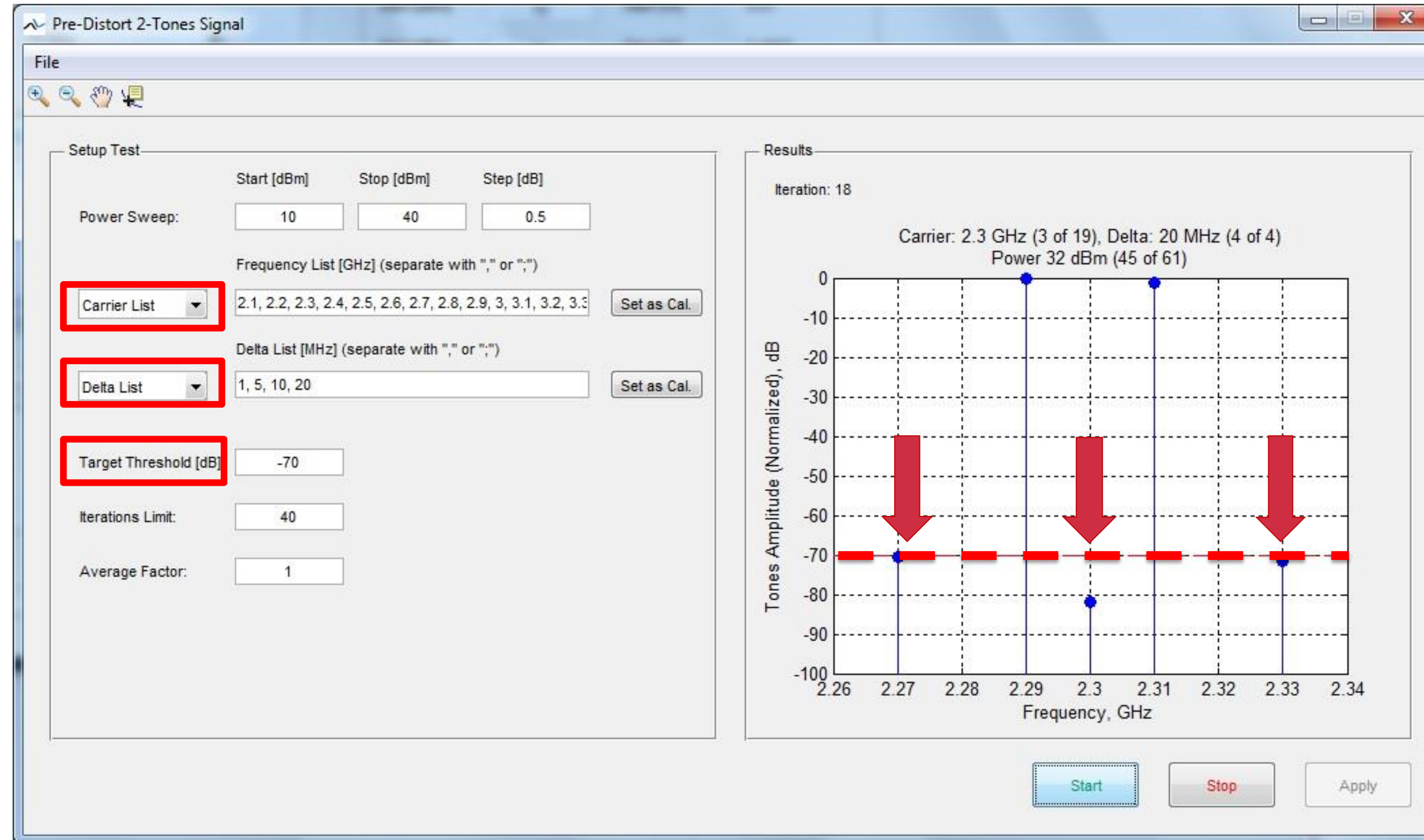
Measured gamma load real time

The impedance of f1 and f2 by active tuning can be converged to desired target, avoiding the phase shift that occurs with passive tuning naturally



Zoom in plot

Pre-distortion calibration to remove the system non-linearity



- *Connect the driving amplifier in the loop*
- *Input the target of minimization*
- *Run the pre-distortion algorithm for each carrier, tone space*
- *It will cost few minutes before test, but **worthy!***

Wideband multi-tones pre-distortion calibration

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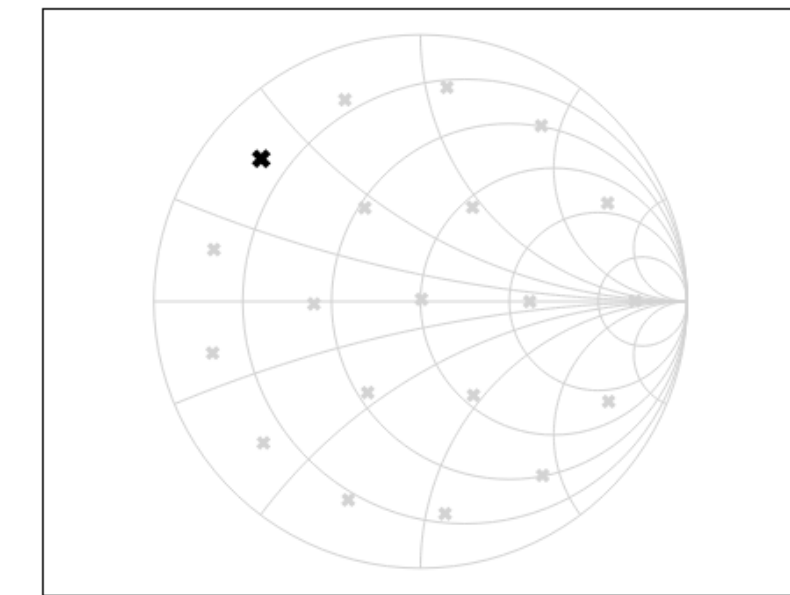
Carrier freq.: 2.6 GHz

Carrier impedance: $0.8 < 110^\circ$

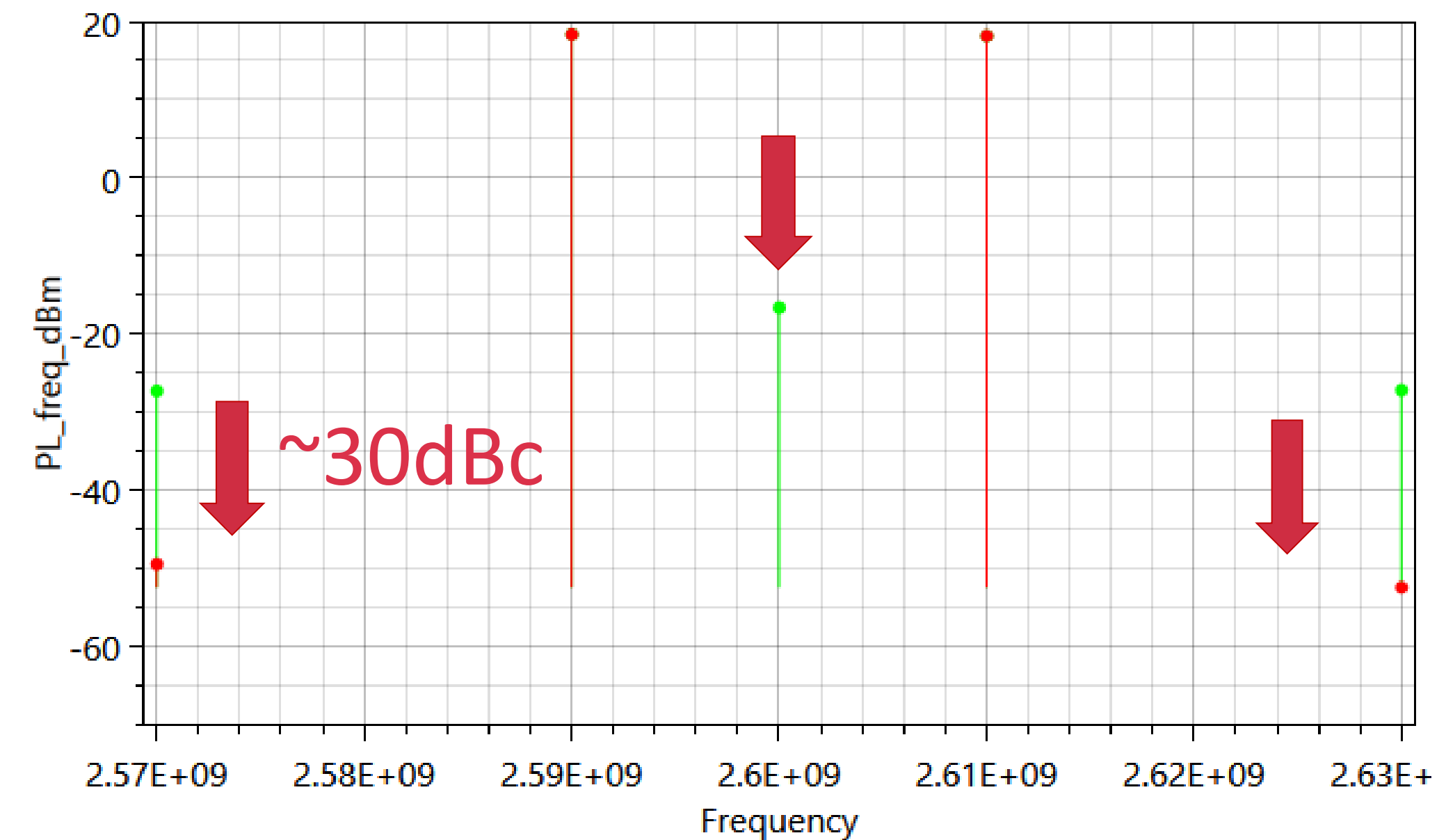
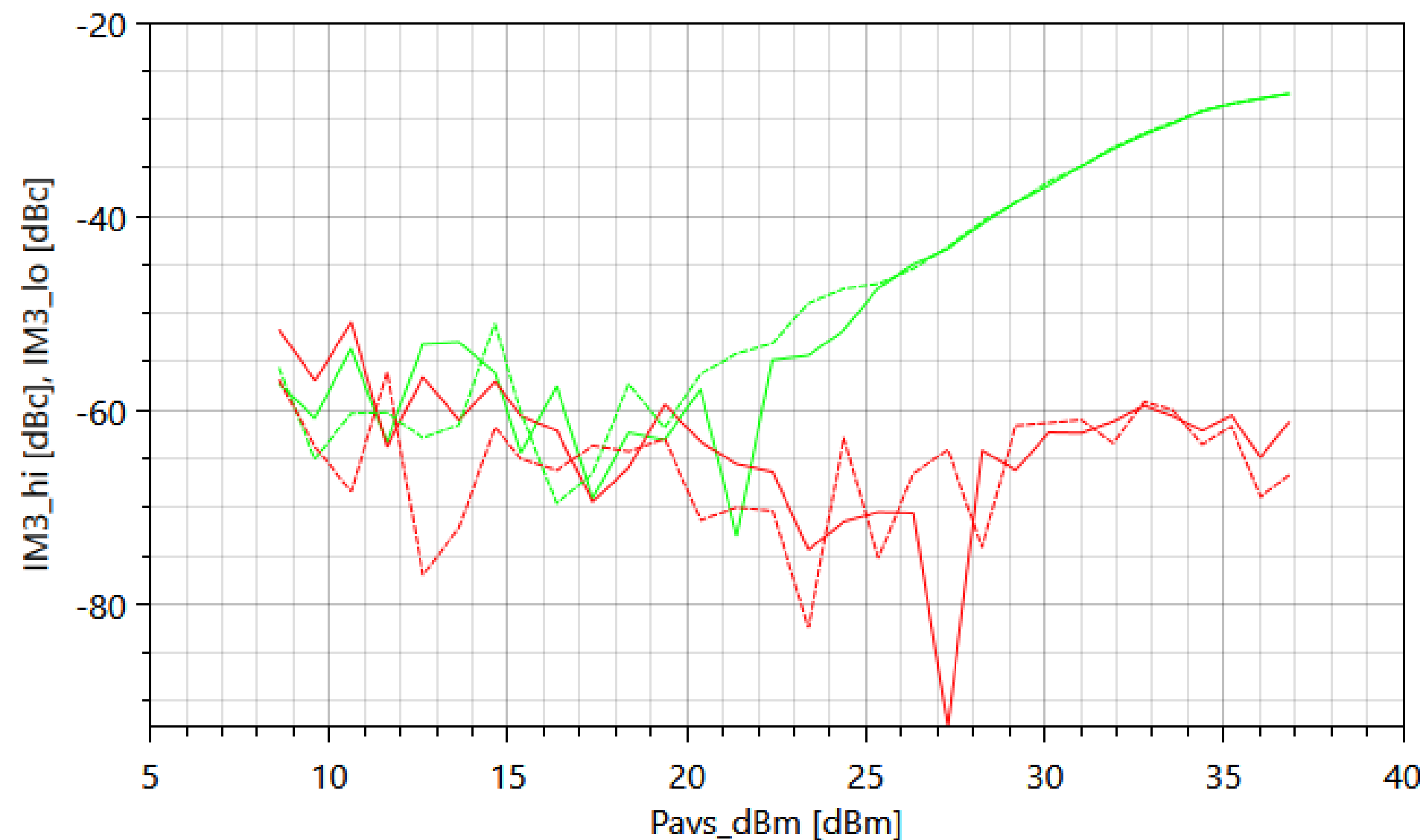
Tone space: 20 MHz

Power sweep: P_{avs} from 3 to 37 dBm (DUT plane)

× Termination
- With pre-distortion
- W/O pre-distortion



Selected termination



With the pre-distortion calibration, the non-linearity of system has been removed completely with the same hardware configuration, **user get greatly improved system capacity without any cost except the calibration time of few minutes!**

- ~~Tuner calibration~~

- > *Not required as there is no mechanical tuner!*

- *Receiver vector calibration*

- > *fast, no sensitive to source and load match.*

- *Receiver power calibration*

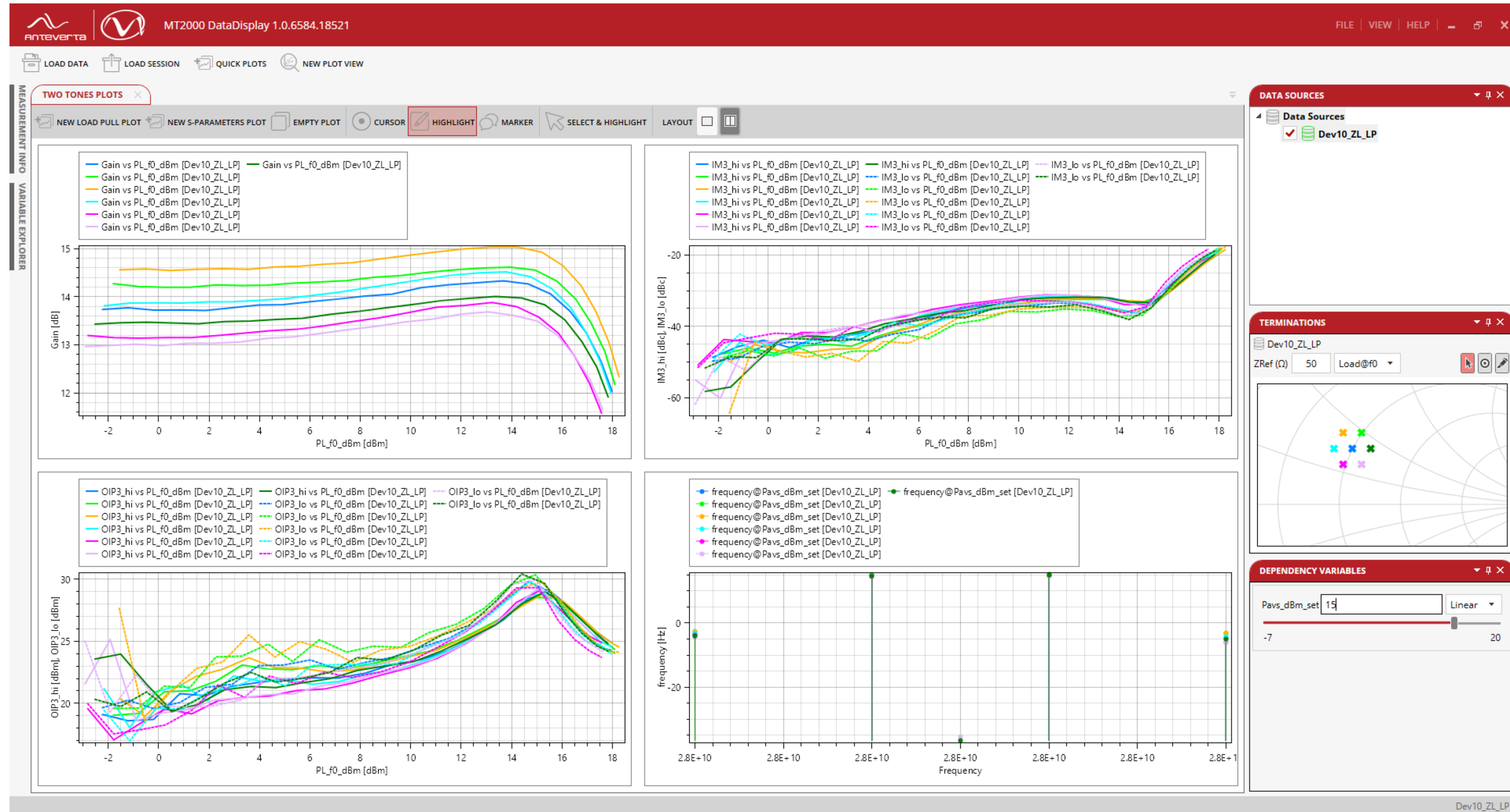
- > *absolute power cal. of receiver by power meter*

- *Pre-distortion calibration with the driving PA*

- > *Improves the linearity of the system*

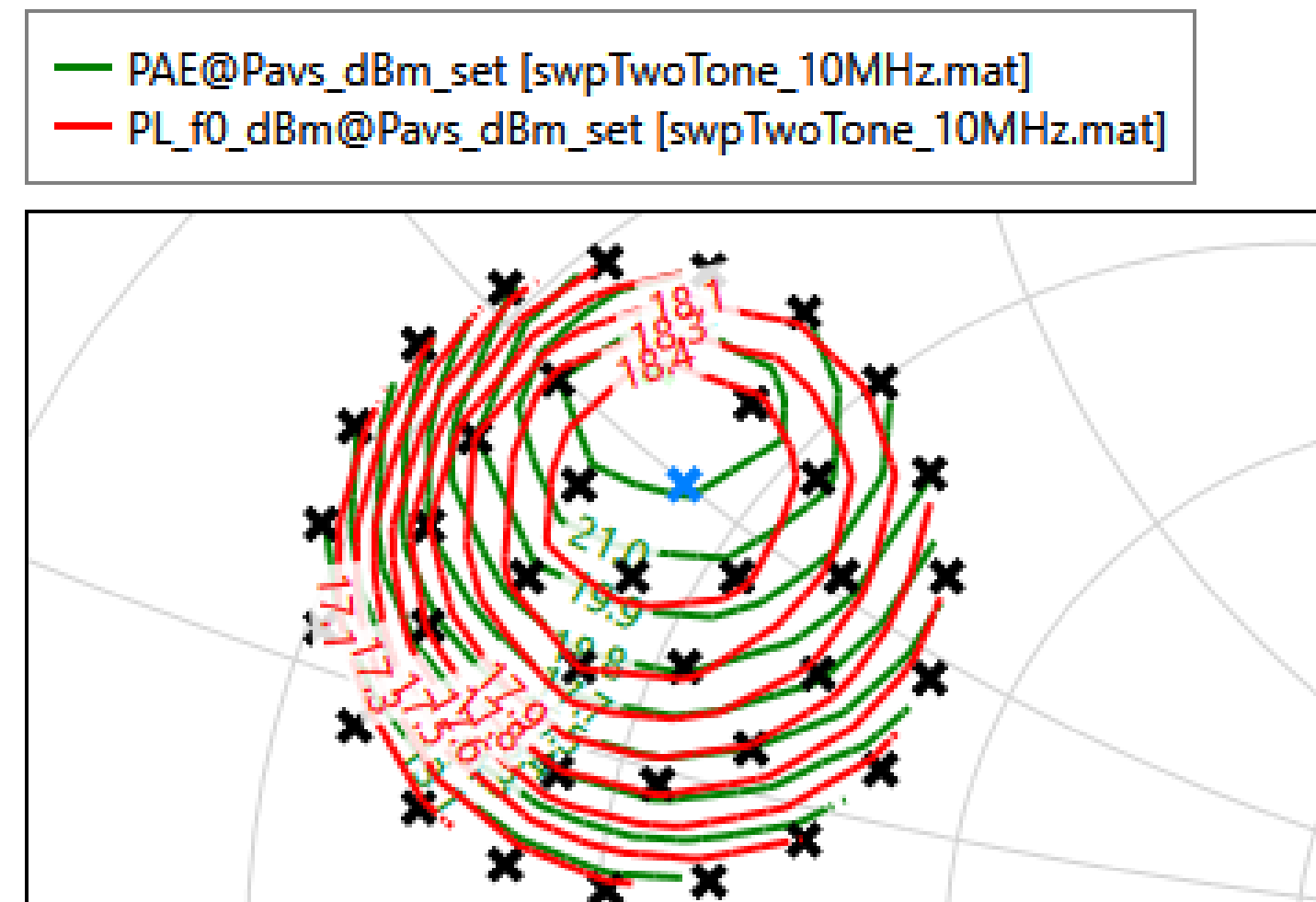
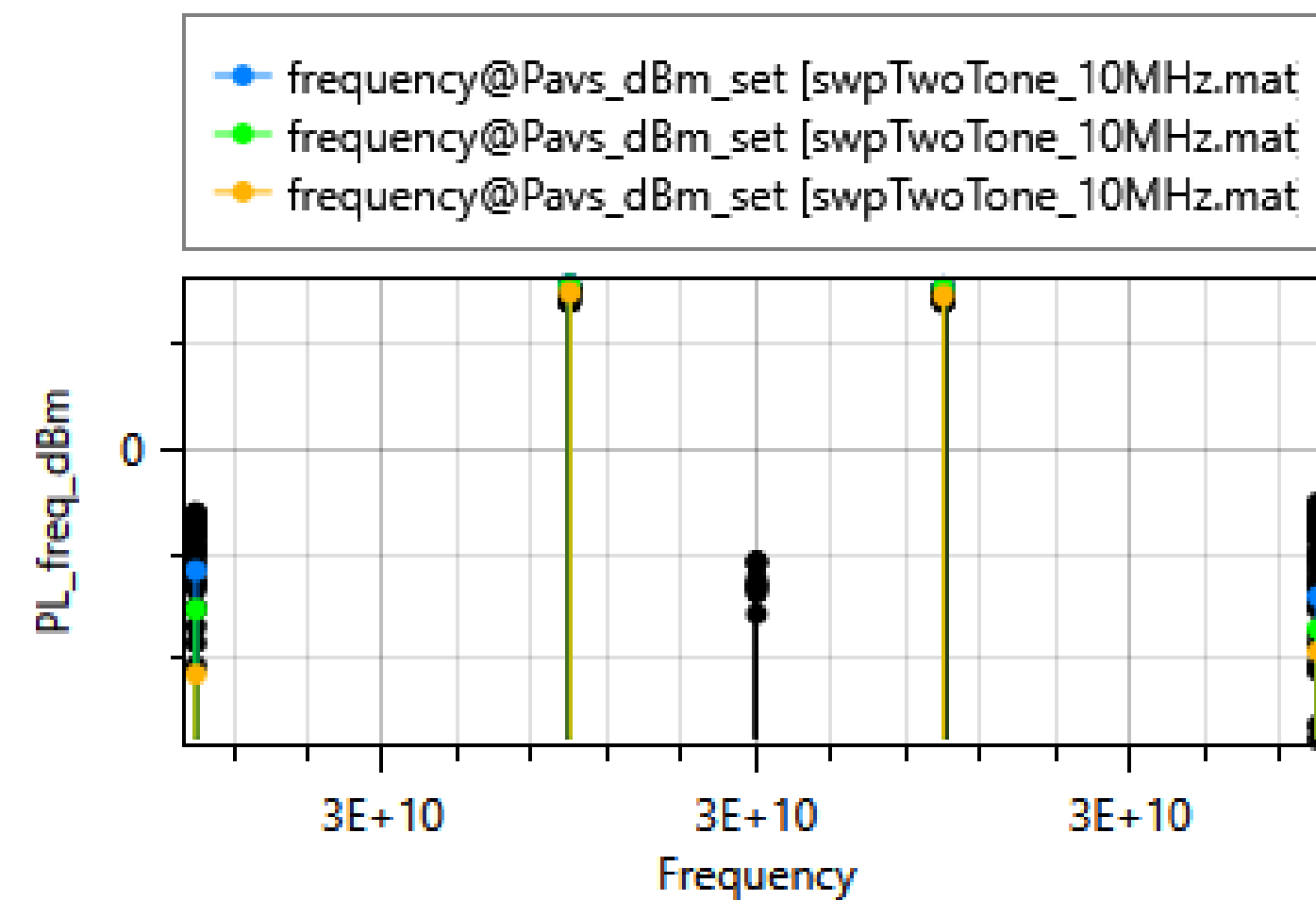
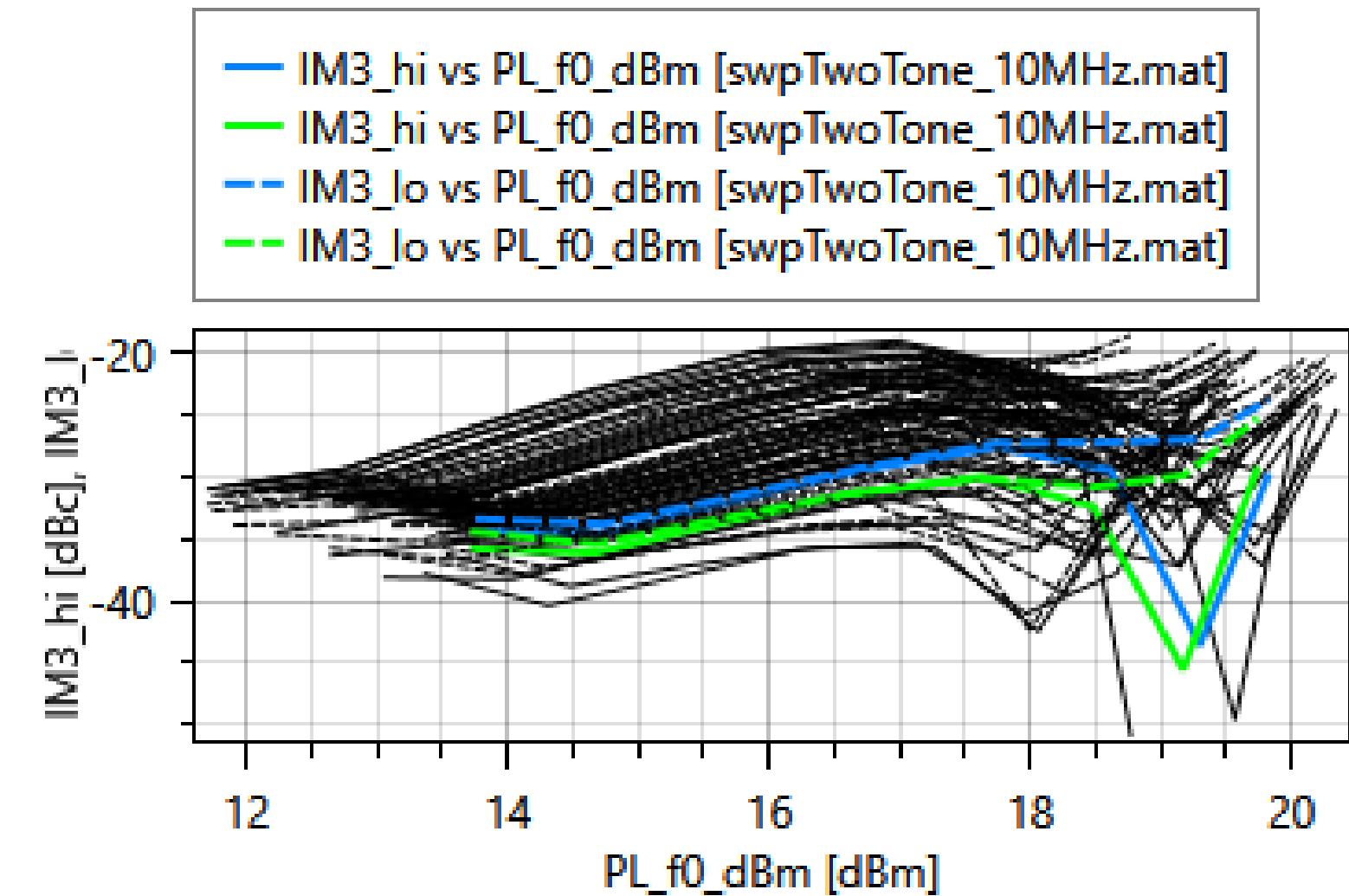
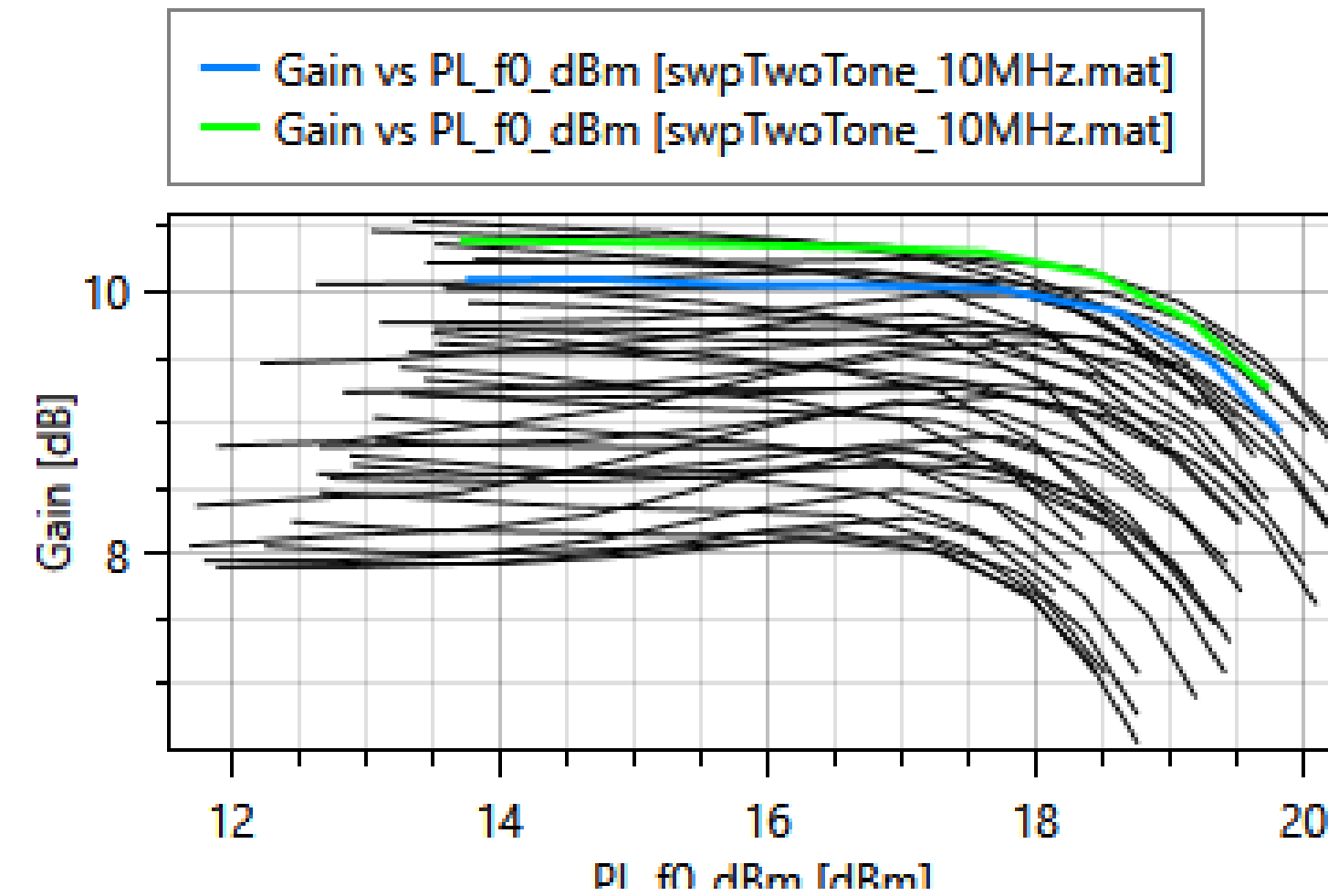
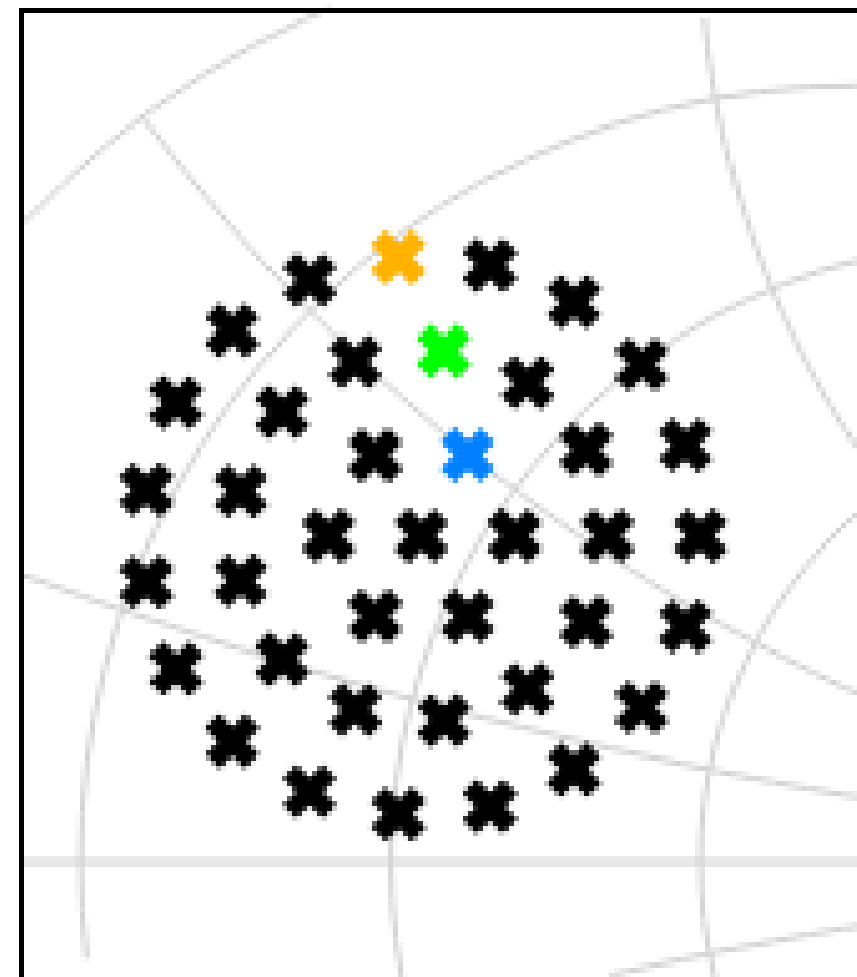
Measurement Example: Two-Tone Load Pull

33



30GHz 2-tone measurement, tone space 10MHz

34



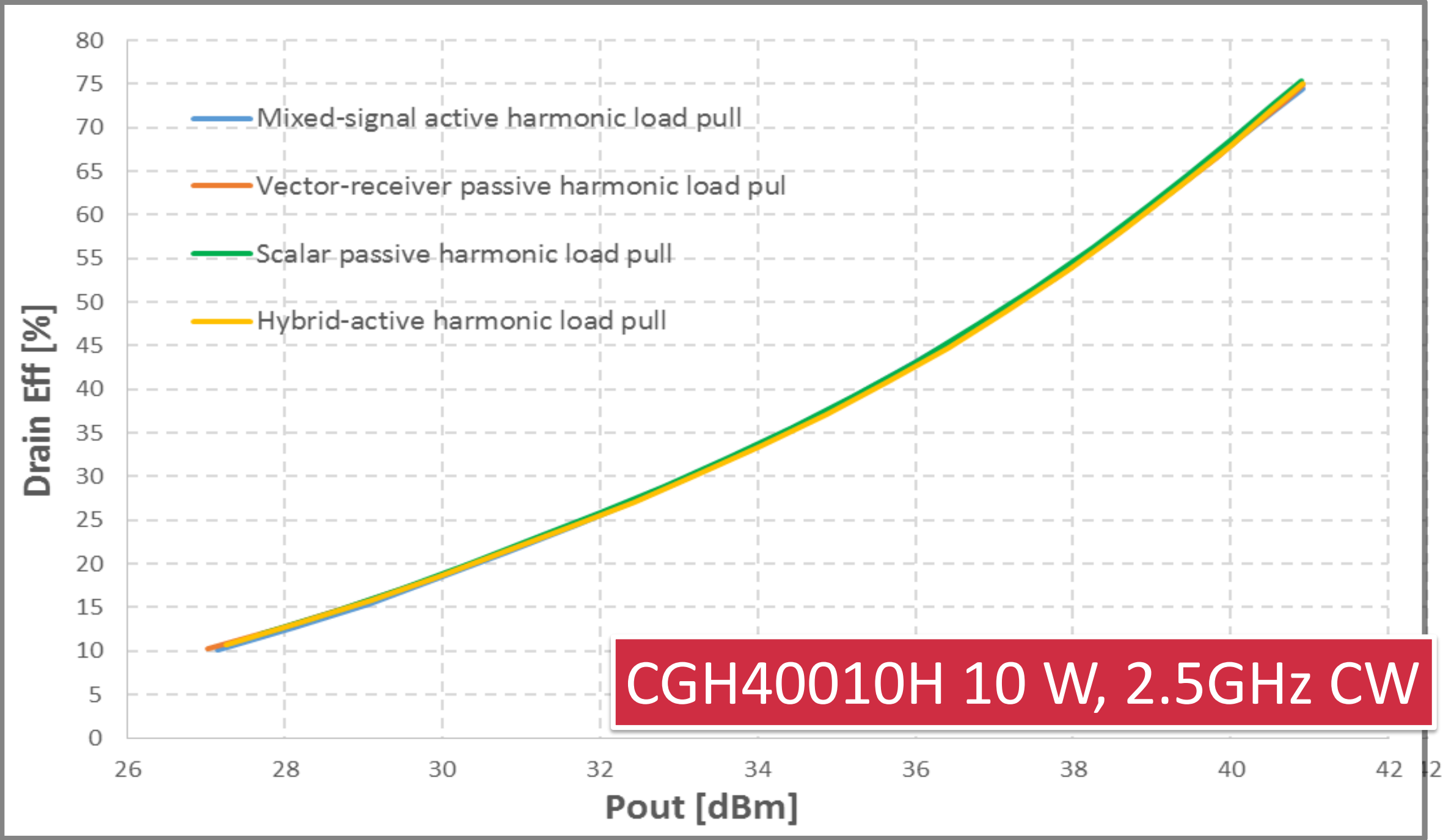
●●●● Summary of MT2000's advantages for 2 tones test

35

A brand-new active architecture for 2 tones in semiconductor industry

- *Baseband signal generation including 2 tone*
- *Pre-distortion calibration algorithm for non-linearity minimization of external driving amplifier and even system*
- *Ultra-broadband tone spacing supported up to 166MHz and more in near future*
- *Ultra-fast calibration and measurement speed*

●●●● Benchmark of MT2000 on same device



| TABLE 1 | | | | | |
|--|-----------|------------|--|--|--|
| COMPARISON OF LOAD-PULL MEASUREMENT TIME (MINUTES UNLESS STATED) | | | | | |
| Setup | Tuner Cal | System Cal | Step 1 | Step 2 | Step 3 |
| | | | f_0 Load-Pull, Fixed $2f_0$ at 50 ohms (35 Loads, 16 Powers) | $2f_0$ Load-Pull, fixed f_0 at Optimized Value (20 Loads, 16 Powers) | f_0 Load-Pull, fixed $2f_0$ at Optimized Value (35 Loads, 16 Powers) |
| Scalar Harmonic (2 tuning elements) | 22 | 3 | 11.1 | 6.4 | 11.1 |
| Vector-Receiver Harmonic (2 tuning elements) | 22 | 5 | 5.3 | 3.1 | 5.3 |
| Hybrid-Active Harmonic (1 tuning element) | 11 | 5 | 4.2 | 7.3 | 7.5 |
| Mixed-Signal Active (0 tuning elements) | No Tuner | 5 | 15 seconds | 35 seconds | 50 seconds |

Beyond active loadpull



In 2010, the MT1000/MT2000 technology was launched as the fastest active load pull system in the world, and the only load pull system capable of controlling impedances over wide bandwidths for modulated measurements

The system architecture required to achieve these breakthrough measurements included the following capabilities:

- VNA capable of measuring CW and pulsed-CW S-parameters
- NVNA capable of measuring time-domain waveforms and load lines
- Multi-tone signal generator/spectrum analyzer combination capable of measuring intermodulation products
- Vector signal generator/analyzer combination capable of measuring ACPR and EVM
- Oscilloscope capable of measuring voltages and currents
- Behavioral model extraction tool capable of black-box and database modeling

While marketed as the world's most advanced load pull system, the MT1000/MT2000 can be used equally as well in 50Ω as in non-50Ω

Most MT1000/MT2000 customers have signed NDAs, however several have published IEEE papers and others have agreed to be contacted as references



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1569864695

Source/Load Pull Investigation of AlGa_N/Ga_N Power Transistors with Ultra-High Efficiency

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Abstract — This paper presents the investigation of highly performing AlGa_N/Ga_N HEMT power transistors through source-pull and load-pull analysis using an active harmonic load-pull system. The advantages of the Ga_N technology together with the right terminations lead to power transistors with promising output power and efficiency. When setting properly the first three output terminations, a drain efficiency as high as 84.3% has been achieved at 2 GHz while delivering 4.3 W of output power for a 1.2 μm device gate width. However, it has been seen that the achievement and the set of the optimum output terminations do not lead to the best device performance. When presenting such three optimum output impedances together with the proper second harmonic source termination, it has been demonstrated that higher drain efficiency up to 88% can be obtained delivering output power as high as 4.4 W and a power gain of 14.9 dB. Indeed the Ga_N HEMT used in this work has reached record peak drain efficiency of 90% delivering output power of 3.5 W.

Index Terms— Aluminum gallium nitride, high efficiency, microwave measurements, power amplifiers, power transistors.

I. INTRODUCTION

POWER AMPLIFIER designs used in wireless communication networks are becoming more and more sophisticated in order to meet the modern requirements. Among the various PA output specifications, one of the most important parameter is still the efficiency. High efficiency means low power consumption and therefore less power dissipated in the environment. In the last decades various PA high efficiency classes have been studied, starting from the more standard class-AB [1-3] going through the switch modes Class-D and Class-E [4-7] to the harmonically tuned modes Class-F and Inverse Class-F [1-3, 8-9]. In these cases the high harmonics can be properly set in order to increase the PA efficiency and therefore minimize the overall power consumption. However, in order to reach certain performances at the PA stage, the device itself and therefore the adopted technology plays a key role in the overall output performance. This paper will show an harmonic load-source pull analysis based on the in house (IAF) highly performed 250 nm AlGa_N/Ga_N power transistors [10-12] for which very high drain efficiency is achieved.

II. ALGaN/GaN TECHNOLOGY

The device used in this work is a HEMT (High Electron Mobility Transistor) power transistor in AlGa_N/Ga_N technology grown on a 3-inch semi-insulating SiC (Silicon Carbide) substrate [10-12] with the photo shown in Fig. 1. The epitaxy of the AlGa_N/Ga_N heterostructure is carried out using multi-source metal organic chemical vapor deposition (MOCVD). In particular the frontside processing involves alloyed Ti/Al/Ni/Au ohmic contacts, implantation isolation and Si₃N₄ passivation assisted T-gates processed by using E-beam lithography as well as a source terminated field plate. Here the device is fabricated with a gate length of L_g=250 nm and a gate width of W_g=1.2 μm (6x200 μm) optimized for high gain, high power density as well as very high efficiency.

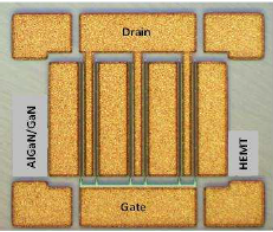


Fig. 1. Microscope photograph of the IAF 1.2 μm AlGa_N/Ga_N HEMT power transistor.

III. LOAD PULL EXPERIMENTAL INVESTIGATION

$Z_{L,F0}, Z_{L,F1}, Z_{L,F2}$

The experimental measurements have been conducted on the 1.2 μm AlGa_N/Ga_N power device described in Section II at 2 GHz of operating fundamental frequency, drain bias voltage V_{DS}=50 V and gate bias voltage V_{GS}=V_{TH}+2.2 V (pinch-off). The measurement system used for testing the Ga_N device and validate the experiment is an active harmonic

Improvements in High Power LDMOS Amplifier Efficiency Realized Through the Application of Mixed-Signal Active Loadpull

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Abstract — This paper presents the results of experimental large-signal characterization of a high power LDMOS amplifier using a mixed-signal active load pull system. The architecture of the system provides the freedom to present unique and independent reflection coefficients at multiple different frequencies. In this case the fundamental frequency, and the 2nd harmonic frequency were chosen, and the reflection coefficients presented to the output terminal of the transistor were captured at these two frequencies. A high voltage LDMOS power amplifier from Freescale Semiconductor was studied and the results will demonstrate that a distinct improvement in drain efficiency is realized through careful magnitude and phase selection of the reflection coefficient at the 2nd harmonic frequency while keeping the reflection coefficient presented at the fundamental frequency at a constant optimized value.

Index Terms — Loadpull, High Power Measurement, Harmonic Tuning, power amplifiers.

I. INTRODUCTION

Loadpull systems that are used to characterize high-power transistors for wireless infrastructure applications continue to be based primarily on mechanical (passive) tuners [1]. This technique has been adopted as the standard for high power applications due to its simple nature compared to alternative approaches and the tuner's ability to handle high pulsed peak-power levels.

While passive tuners have many advantages one disadvantage is the lack of control over reflection coefficients presented by the tuner at uncalibrated frequencies [2]. Passive tuners are designed to have very high quality factors which allow them to present a high reflection coefficient to the device under test. This very desirable trait, however, reduces the tuning range to a very small frequency bandwidth [2]. Energy that is generated or reflected by the device under test (DUT) at the uncalibrated frequencies will be partially absorbed and partially re-reflected by the tuners in a manner that cannot be pre-determined. As a result, any changes to the devices behavior due to this stray energy could potentially lead to inaccurate device characterization or misunderstanding of device behavior [2].

Several innovative passive techniques that allow for calibration and impedance control at multiple frequencies (mostly the harmonic frequencies) have become commercially available over the past several years. These systems accomplish harmonic manipulation by adding additional

tuners for each harmonic frequency either in cascade or through a network of filters in the form of a diplexer or triplexer [3,4].

In the case of cascaded tuners there are simply additional tuners (or resonators within the same tuner) that are placed between the DUT and the fundamental tuner. The cascaded resonators work in conjunction with each other to provide the desired reflection coefficient magnitude and phase for each frequency of interest. The benefit of this approach is the relatively similar set up and operation compared to a standard passive loadpull configuration. The disadvantages are the increased insertion loss between the DUT and the fundamental tuner and poor isolation between the multiple resonators. High isolation between resonators within the same tuner can be achieved within very narrow bandwidths.

In the case of the diplexer/triplexer configuration multiple tuners are given a direct connection to the DUT via filters that direct the signals to the appropriate tuners based on frequency. The configuration of this system is relatively complicated and is limited to the availability of diplexers and triplexers that can be purchased for the frequency bands of interest. The benefit is highly isolated control of the harmonic frequencies with only small insertion losses.

While effective, these approaches require additional peripheral hardware and characterization time. Automated mechanical tuners with high gamma capabilities can also be expensive to purchase and maintain. Active load pull has become a popular choice for wide band and multi-harmonic tuning. Standard system architectures can support multiple frequency agnostic loops for tuning while stray energy generated within the system is terminated with the characteristic impedance of the system. Open loop active load pull systems are also capable of accommodating relatively large signal bandwidths due to the impedance being presented to the device under test being completely synthesized [2].

II. MIXED-SIGNAL HARMONIC LOADPULL

The high data traffic on today's cellular networks has created demand for a power amplifier that is both linear and efficient. LDMOS power amplifiers biased in class AB and class B offer acceptable theoretical efficiencies along with distortion products that can be sufficiently corrected using appropriate impedance matching or digital pre-distortion

DESIGN OF AN ULTRA-EFFICIENT GAN HIGH POWER AMPLIFIER FOR RADAR FRONT-ENDS USING ACTIVE HARMONIC LOAD-PULL

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Keywords: GaN Power Amplifier, Active Load-pull, Harmonic tuning

Abstract

This work presents a new measurement technique, mixed-signal active harmonic load-pull (MSALP) developed by Antevorta-mv in partnership with Maury Microwave, that allows for wide-band ultra-high efficiency amplifiers to be designed using GaN technology. An overview of the theory behind active load-pull is presented and why load-pull is important for high-power device characterization. In addition, an example procedure is presented that outlines a methodology for amplifier design using this measurement system. Lastly, measured results of a 10W GaN amplifier are presented. This work aims to highlight the benefit of using this sophisticated measurement systems for to optimize amplifier design for real radar waveforms that in turn will simplify implementation of space-based radar systems.

1. Introduction

GaN devices are increasingly becoming an enabling technology for advanced space-based radar systems. The use of GaN allows for improved system performance due to its high efficiency and output power. In addition, the adoption of GaN into commercial applications, such as cell phone base stations has allowed the technology to mature and improve reliability and device performance.

Such high priority missions as the proposed Earth Radar Mission's (ERM) DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) SAR Instrument (DSI) utilizing the SweepSAR concept are made feasible by the use of high power, high efficiency solid state power amplifiers [1, 2]. In the design concepts for this mission, multiple high power TRM (transmit/receive modules) (> 100 W output power) that are thermally managed by the surface area of the TRM acting as the thermal radiator. For typical duty cycles and efficiencies, over 20 W of power must be dissipated by this surface, requiring extremely large TRM, which are not suitable for this space borne system.

GaN technology presents two benefits for the proposed DSI: (1) a potential reduction of thermal stresses due to increased efficiency and (2) ability to operate at higher junction temperatures. By easing the thermal requirement, the radiator size may be decreased allowing for a more compact TRM, reducing mission costs. In order to fully op-

timize the high power amplifier design using GaN HEMT technology, the new characterization technique, active harmonic load-pull, is being developed to increase efficiencies and reduce harmonic levels over a wide-band [3]. Though tuning load and harmonic impedances Class-J current and voltage waveforms can be engineered that provide optimal balance between performance, bandwidth, and linear response. There is increasingly more literature on the use of these systems for designing amplifiers for use with modulated telecommunications signals, but to the authors knowledge, no work has been demonstrated this technique for typical radar signals.

This work will present an overview of a wide-band mixed signal active harmonic load-pull system (MSALPS) [4] that is capable of harmonic tuning over a real radar waveform (such as a chirp) to optimize amplifier performance and efficiencies to > 70 %. This system was developed by Antevorta-mv in partnership with Maury Microwave and a detailed discussion of the load-pull system is presented in [5]. Section I will provide an overview the theory behind the MSALPS system and the specific measurement setup used for amplifier characterization. Section 2 will present a design overview of an L-band GaN amplifier for use in the proposed DSI TRM with the measured results of this design presented in section 3.

2. Mixed-Signal Active Load-pull Measurement Overview

The basic concept of "load-pull" is to present known impedances to devices under test (DUT) in order to determine their characteristic response, enabling performance optimization for non-linear devices. Fig. 1 shows the signal flow graph for a non-linear two-port device where $a_{1,2}$ represent the incident waves and $b_{1,2}$ are the reflected waves. S_{xx}^* represents the large signal S-parameters of the DUT. For a small-signal network analyzer, the DUT is insensitive to load impedance and therefore standard VNA error correction terms can be used to calibrate to the reference plane of the device to extract S-parameters. However, for large signal conditions, load-pull is necessary since the DUT is no longer linear and therefore linear superposition and simple two-port network theory is not valid. Impedance tuners allow a simulated Γ_L presented to the device and enables the measurements of the non-linear large-signal S-parameters.

Design of an Ultra-High Efficiency GaN High-Power Amplifier for SAR Remote Sensing

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Abstract—This work describes the development of a high-power amplifier for use with a remote sensing SAR system. The amplifier is intended to meet the requirements for the SweepSAR technique for use in the proposed DESDynI SAR instrument. In order to optimize the amplifier design, active load-pull technique is employed to provide harmonic tuning to provide efficiency improvements. In addition, some of the techniques to overcome the challenges of load-pulling high power devices are presented. The design amplifier was measured to have 49 dBm of output power with 75% PAE, which is suitable to meet the proposed system requirements.

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| 3 LOAD-PULLING HIGH POWER TRANSISTORS | 3 |
| 4 HIGH POWER AMPLIFIER DESIGN | 4 |
| 5 SUMMARY | 5 |
| REFERENCES | 6 |
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I. INTRODUCTION

Requirements for next generation SAR remote sensing systems demand new technology to allow these systems to be feasible. Increased swath size, high resolution, rapid global coverage, as well as sub-cm interferometry and polarimetry require advanced techniques such as SweepSAR, which would be employed by the proposed Earth Radar Mission's (ERM) DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) SAR Instrument (DSI). SweepSAR would use multiple transmit/receive (T/R) channels and digital beamforming to achieving simultaneously high resolution and large swath [1].

The SweepSAR technique (Fig. 1) would use a large aperture reflector with a linear patch feed array, with each set of patches fed by a single T/R module. On transmit, all T/R modules would be used in unison, sub-illuminating the reflector creating a large swath on the ground. While on receive, individual beams would be formed by stitching multiple receivers together using digital beamforming [2]. This technique would produce, for transmit, an electrically small antenna, illuminating a large area on the ground, while on receive, smaller beams would be formed, yielding higher resolution. Due to the large swath, a receiver would have

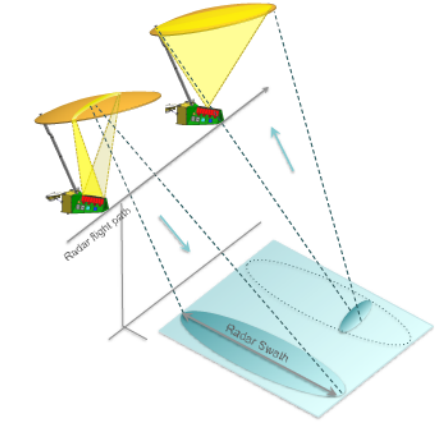


Figure 1. SweepSAR technique highlighting transmit and receive operation. Beamforming on transmit would produce a single large beam covering a wide-swath. Digital beamforming on receive would allow for multiple high resolution beams.

valid data across many transmit events, therefore, any transmit event would cause a loss of science data (gaps in the swath). Therefore, the transmit pulse width should be narrow as possible, limiting the total amount of power available to illuminated the ground. However, due to the size of the swath, the transmit energy would be spread over a large area, which would demand a longer pulse width and higher peak transmit power. A longer pulse width is not an option, therefore, multiple high-power T/R modules would be required.

Previous generations of high-power amplifiers for use in remote sensing applications utilized GaAs and Si Bipolar transistors and are not suitable for large arrays containing multiple high-power amplifiers. However, Gallium Nitride (GaN) High Electron mobility transistors (HEMTs) are an emerging technology that offers high-power density as well as high efficiency, making them an effective solution for SweepSAR applications. The high breakdown voltage of GaN as well as its excellent thermal properties make it a perfect candidate for high-power amplifiers [3]. For commercial applications, GaN has begun to become the technology of choice for RF transmitters in a variety of market segments.

U.S. Patent No. 8,456,175 B2
Several international patents also available



System Offering



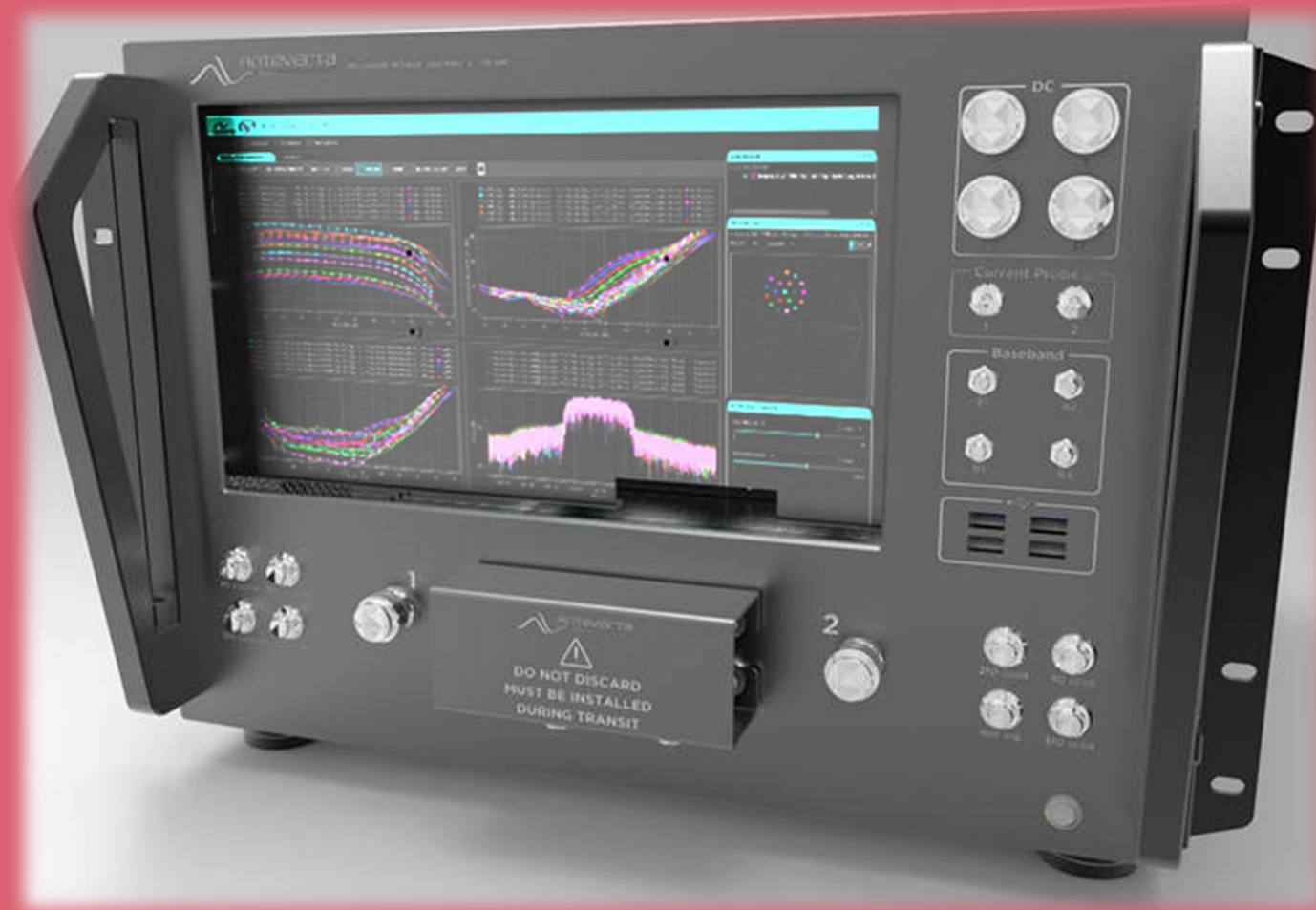
Five Frequency Range are available: Five options of Active Tuning loops are available:

- ❖ 0.001 – 2 GHz (50W CW, 500W Pulsed)
 - ❖ 0.03 – 2 GHz (50 CW, 500W Pulsed)
 - ❖ 0.3 – 6 GHz (100W CW, 1000W Pulsed)
 - ❖ 0.2 – 18 GHz (100W CW, 1000W Pulsed)
 - ❖ 0.7 – 40 GHz (20W CW, 200W Pulsed)
- ❖ 2 loops $s(f_0$ source/load pull)
 - ❖ 3 loops (f_0 , $2f_0$ source/load pull)
 - ❖ 4 loops (f_0 , $2f_0$ and $3f_0$ source/load pull with 4 of 6 possible combinations)
 - ❖ 5 loops (f_0 , $2f_0$ and $3f_0$ source/load pull with 5 of 6 possible combinations)
 - ❖ 6 loops (f_0 , $2f_0$ and $3f_0$ source/load pull)

Three Modulation Bandwidth options are currently available (MT2000 only):

- ❖ 100 MHz
- ❖ 200 MHz
- ❖ 500 MHz
- ❖ 2019 – 1 GHz

Note: MT1000 series doesn't support two tones and modulated measurements



MT1000/2000 take you beyond the VNA!

Thank You!



For more info. Pls. visit:

https://www.maurymw.com/MW_RF/Mixed_Signal_Active_Load_Pull_System.php